Intelligent Reliability Analysis

Using

MATLAB and AI

Perform Failure Analysis and Reliability Engineering using MATLAB and Artificial Intelligence



DR. CHERRY BHARGAVA
DR. PARDEEP KUMAR SHARMA

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Dr. Cherry Bhargava

Dr. Pardeep Kumar Sharma



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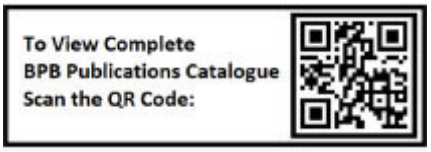
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Dedicated to

Our Parents

&

Our Loving Daughters, Mishty & Mauli

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At this moment of my substantial enhancement, before we get into the thick of the things, we would like to add a few heartfelt words for the people who gave their unending support with their fair humor and warm wishes. First and foremost, praises and thanks to the God, the Almighty, for his showers of blessings throughout, to complete this book successfully. We want to acknowledge our students who provided us with the impetus to write a more suitable text. We are thankful to the management, seniors, and colleagues of Symbiosis International University and Lovely Professional University for constantly pushing us to move higher and higher. We would also like to thank all our friends, well-wishers, respondents, and academicians who us helped throughout our journey from inception to completion.

Preface

Due to the rapid evolution of the electronics device technology towards low cost and high performance, the electronic products become more complex, higher in density and speed, and lighter for easy portability. Reliability has become the major issue for the successful operation of an electronic device. During the life cycle of a component, reliability needs to be accessed at its different stages of life, i.e., at the design stage, manufacturing stage, launching stage, and operational stage. So, the assessing of the component performance at the different phases are necessary. After analyzing all the factors and parameters, the warranty period is extracted, which is mentioned along with the data sheet. The failure analysis explores the root cause of failure and then suggests the preventive and corrective measures, so that the overall performance of the system will not degrade.

This book focuses on the failure analysis and fault prediction techniques using Artificial Intelligence. The failure prediction warns the user to replace the faulty component or the device before it deteriorates the entire system. It explores the residual life of the respective component or device in terms of the mean time between failure or the end of lifetime. To predict failure of any component or device, enormous methods and models have been used, i.e., the empirical method, analytical method, theoretical methods, experimental method, and artificial intelligence techniques etc. The necessary corrective actions for the failure of the electronic components are discussed in this book, using various examples.

Over the 7 chapters in this book, you will learn the following:

Chapter 1: [RELIABILITY FUNDAMENTALS]

This chapter emphasises upon the fundamentals of reliability and life analysis. The concept of faults, failures, and errors are described using examples. The reliable data acquisition in the wireless sensor networks are discussed.

Chapter 2: [RELIABILITY MEASURES]

This chapter explains the importance of Reliability, Availability, Validity, and Maintainability. The need for the reliability analysis and prediction is discussed by considering examples of the various electronic components.

Chapter 3: [REMAINING USEFUL LIFETIME ESTIMATION TECHNIQUES]

This chapter discusses the significance of the Remaining Useful Lifetime and the concept of e-waste minimization. The various empirical, experimental, and mathematical models for the RUL prediction are discussed along with the applications.

Chapter 4: [INTELLIGENT MODELS FOR RELIABILITY PREDICTION]

This chapter explains about the application of the artificial intelligence techniques for the reliability prediction and the RUL estimation. An intelligent model is deployed, which warns the user for the upcoming fault or failure, so that the user can replace the faulty product well before its expiry/actual failure.

Chapter 5: [ACCELERATED LIFE TESTING]

This chapter discusses the experimental approach for analyzing the reliability and residual lifetime of the electronic components. An Arrhenius equation based accelerated life testing method is used as an experimental technique. The design of experiments is conducted using the Taguchi's method for the electrolytic capacitor.

Chapter 6: [EXPERIMENTAL TESTING OF ACTIVE AND PASSIVE COMPONENTS]

This chapter explains the experimental test approach for the reliability analysis using examples of the various active and passive electronic components. The calculation of the different reliability parameters such as FIT, MTBF, and reliability are elaborated in this chapter.

Chapter 7: [INTELLIGENT MODELLING FOR RELIABILITY ASSESMENT USING MATLAB]

This chapter explains the MATLAB based intelligent modelling for the reliability assessment of the various active and passive components, such as the capacitor, resistor, or inductor. The

Artificial Neural Network (ANN), Fuzzy Logic (FL), and Adaptive Neuro-Fuzzy Inference System (ANFIS) are explored for the reliability prediction of the electronic components.

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Table of Contents

1. Reliability Fundamentals

Introduction

Structure

Objectives

Reliability

Failure

Role of probability laws in reliability theory

Hazard rate

Weibull distribution

Some important measures related to reliability analysis

Probability of survival

Mean Time Between Failures [E(T)]

Failure rate or Hazard rate

Hazard function [h(t)]

Failure density function [f(t)]

Configuration in the context of reliability analysis

Series configuration

Parallel configuration

Mixed configuration

Series-parallel configuration

Parallel-series configuration

Reliability analysis of Wireless Sensor Networks

Wireless Sensor Networks and data acquisition systems

Constraints of Wireless Sensor Networks

Methods for Wireless Sensor Networks

Evolution of Wireless Sensor and Actuator networks

Centralized decision-making architecture

Distributed decision-making architecture

Modes of Data Acquisition
Reliable Data Acquisition
Issues in reliable data acquisition
Application areas of reliability
Conclusion
Questions

2. Reliability Measures
Introduction
Structure
Objectives
Introduction
Definition and scope of reliability
Probability
Adequate performance
Specified time
Operating conditions
Reliability measures
Reliability
Maintainability
Availability
Point availability
Mean availability
Steady state availability
Inherent availability
Achieved availability
Operational availability
Mean Time to Failure (MTTF)
Mean Time to Repair (MTTR)
Mean Time Between Failure (MTBF)

Mean Time Between Maintenance (MTBM)
Expected profit
Sensitivity Analysis
Systems
Repairable systems
Non-repairable systems
Failures and Failure modes
Defects in the designing of the component
Operating conditions
Major Failure
Minor Failure
Common Cause Failure
Catastrophic Failure
Human Error
Failure Frequencies
Failure density
Failure rate
Conditional Failure Intensity
Maintenance
Methodology used
Markov model
Supplementary variable technique
Laplace Transformation
Need forreliability analysis
Electronic components failure mode and mechanism
Conclusion
Questions

3. Remaining Useful Lifetime Estimation Techniques
Introduction

Structure
Objectives
Importance of failure prediction
Reuse
Component reuse
Merits of component reuse
Failure prediction of electronic components
Techniques for RUL prediction
Selection of component for failure assessment
Collection of failure data
Failure prediction using artificial intelligence techniques
Comparison of techniques
Mathematical model
Electrolytic capacitor
Behaviour analysis of electrolytic capacitor
Effect of temperature on lifetime of capacitor
Effect of voltage on lifetime of electrolytic capacitor
Effect of ripple current on lifetime of electrolytic capacitor
Effect of ESR on lifetime of electrolytic capacitor
Effect of humidity on lifetime of electrolytic capacitor
Mathematical modelling of electrolytic capacitor
Statistical technique
Empirical methods for RUL
Case study of electrolytic capacitor
Failure prediction of electrolytic capacitor using mathematical model
Lifetime prediction of electrolytic capacitor using regression
Conclusion
Questions

4. Intelligent Models for Reliability Prediction

Structure
Objectives
Introduction
Artificial neural network technique
Structure of the neural network
Fuzzy logic technique
Adaptive Neuro Fuzzy Inference System
Decision Support System
Case study of electrolytic capacitor
Calculation of lifetime using neural networks
Training fuzzy logic model
Calculation of electrolytic capacitor lifetime using fuzzy logic model
Failure prediction using adaptive neuro-fuzzy inference system model
Conclusion
Questions

5. Accelerated Life Testing
Introduction
Structure
Objectives
Importance of accelerated life testing
Experimental approach for the failure prediction of the electrolytic capacitor
Materials and methods
Determination of the experimental parameters: A DOE approach
Selection of the factors for the study
Selection of the number of levels for the factors

Selection of the appropriate orthogonal array
Assignment of the factors to the columns
Conduct of the test
Analysis of the failure time

Analytical approach for the failure prediction of the electrolytic capacitor
Error analysis of the analytical failure prediction model of an electrolytic capacitor
Experimental approach for the failure prediction of the humidity sensor
Failure prediction of the humidity sensor
Conclusion
Questions

6. Experimental Testing of Active and Passive Components
Structure
Objectives
Accuracy estimation and error analysis
Evaluation of the reliability of the humidity sensor DHT11
Procedure for the experimental testing of the humidity sensor
Evaluation of the reliability of temperature sensor LM35
Procedure for experimental testing
Evaluation of the reliability of an electrolytic capacitor
Procedure for experimental testing
Evaluation of the reliability of Carbon Film Resistor
Procedure for experimental testing
Evaluation of the reliability of PN Junction diode
Procedure for experimental testing
Evaluation of the reliability of Bipolar Junction Transistor
Procedure for experimental testing

Evaluation of the reliability of thermistor
Procedure for experimental testing
Evaluation of the reliability of thyristor
Procedure for experimental testing
Evaluation of the reliability of 555 Timer IC

Procedure for experimental testing
Evaluation of the reliability of operational amplifier
Procedure for experimental testing
Cautions to be followed in experiments
Observation tables
Conclusion
Questions

7. Intelligent Modelling For Reliability Assessment Using MATLAB
Structure
Objectives
Artificial Intelligence: A tool for reliability estimation
Reliability Assessment Using Artificial Neural Networks (ANN)
Reliability Assessment Using Fuzzy Logic (FL)
Conclusion
Questions

Index

CHAPTER 1

Reliability Fundamentals

Introduction

The reliability theory was introduced during the World War II, and it plays a critical role in systems design and development. A valuable contribution was made to the development of the theory of reliability by the mathematicians like Gnedenkov, Belgayev, Solovyeu, Polovoko, Barlow, and Proschan.

Structure

In this chapter, we will discuss the following topics:

Importance of reliability and life analysis

Faults and failures

Various configuration of reliability system

Series, parallel, and hybrid arrangement

Reliable data acquisition in wireless sensor networks

Objectives

After studying this chapter, students should be able to understand the basic concepts of reliability, application area, and its performance parameters. The need of reliability for electrical and electronics components and devices is specified in this chapter. It would help the students to differentiate between faults, defects, and failures. The fundamental techniques and methods for reliability assessment and condition monitoring are discussed.

Reliability

In the modern era of integration, millions of transistors and other electronic components are connected on a single chip. As the number of devices enhance, reliability and validity become a challenging and critical issue. In a series connection, if any one of the components fails or degrades its performance, the complete system shuts down immediately. So, reliability analysis of all the individual components are equally important and necessary for the long term quality performance of the complete device or system.

The efficiency of the system which is performing a specific task, is described by the terms such as reliability, survivability. Reliability means the ability of the system to perform its intended function satisfactorily. The term **reliability** was defined by the **Advisory Group on Reliability of Electronic Equipment** as the *"probability of a product performing its intended function satisfactorily under given condition for a specified period of* The reliability evaluation techniques were adopted mostly in military applications and aerospace industry for the improvement of quality. The improvement of the effectiveness of components of various kinds has received special attention concerning with numerous problems because of the advanced technology. Sometimes effectiveness is also referred to as *quality* in literature.

The concept of **survivability** is understood as the ability of the system to preserve the properties to serve its purpose under adverse conditions (viz, explosions, fine, inundation, and so on). The reliability of a system was determined by the properties of the system, namely, trouble proofness, reparability, and longevity. **Trouble proofness** is the property of a system to preserve its capability in the duration of a definite time under normal conditions. The prevention, detection, and elimination of failure are useful for improvement of the system that is called **Longevity** is the ability for a prolonged operation with the necessary technical maintenance including various kinds of repairs. **Maintainability** is defined as the probability that failed equipment is restored to operable condition in a specified time (known as down time). **Availability** is the measure of performance of repairable equipment. It is the combination of reliability and maintainability.

Failure

The word failure plays an important role in the context of reliability theory. The term **failure** is defined as the termination of the ability of an item to perform its intended function. The notion of failure is a useful characteristic of reliability analysis because it is mainly responsible for various numerical criteria of reliability analysis. Failures are classified into the following different ways – inherent weakness failure, sudden failure, gradual failure, catastrophic failure, and degradation failure. Some of the causes for failures of component in the system are poor designing of the components, lack of experience, poor maintenance policies, wrong manufacturing techniques, and human errors.

Role of probability laws in reliability theory

The **reliability analysis** of a system is based precisely on defined concepts like reliability function R (t), expected life E (T), hazard function h (t) and failure rate λ (t). A population of identical systems, which operate under identical conditions, fail at different duration of times and the failure phenomenon can only be described in probability terms. Thus, the reliability definition is based on the concept of probability theory. In practice, reliability evaluation is associated with some parameters which are described by probability distributions. The most useful continuous distributions in the theory of reliability are the exponential, weibull, gamma, normal, and log normal distributions, and the two most important discrete distributions are binomial and poisson.

Hazard rate

In the reliability theory, identifying failure model is an art. The concept of **hazard rate** is effectively used in reliability analysis to identify the failure distributions. For instance, if the hazard rate is more or less constant, then it would represent that time to failure follows exponential distribution. The exponential distribution is widely used in the theory of reliability. On the other hand, it is interesting to note that exponential distribution would arise as a particular case of weibull and gamma distributions which are most commonly used in life testing and reliability estimation.

Weibull distribution

Weibull distribution was named after the Swedish scientist Weibull, who proposed it for the first time in 1939 in connection with his studies on strength of materials. Weibull established that the distribution is also useful in describing the aging effect or wear-out failures KAO, proposing it as a failure model for vacuum tube failures, and Leiblin and Zelen used it for ball bearing failures. Mann et al has shown the number of situations where this model is applicable for other types of failure data. Normal distribution is also applicable as a failure model in the context of reliability. Davis observed that the failure data is fit to normal distribution in the case of incandescent lamps; Bozavsky also described the use of the normal distribution in reliability problems.

Some important measures related to reliability analysis

Reliability measures quantify the effectiveness of the system. In the reliability theory, some of the important measures are covered in the next sections.

Probability of survival

The **probability of failure** is similar to that of **probability of** The probability of survival is defined as the probability of a system operating without failure for a required period of time Y, and is given by the following formula:

$$P(T > t) = 1 - F(t)$$

Here, T is a random variable representing time to failure of the system, F (t) indicates the probability of the system failing by the time Y, and is defined as failure distribution.

Mean Time Between Failures [E(T)]

The definition of **Mean Time Between Failure** is the average time taken between any two failures of system. This is usually the mathematical expected value of time to failure of the system.

$$E(t) = \int_0^\infty t.f(t)\,dt$$

$$E(t) = \int_0^\infty R(t)\,dt$$

Here, f(t) and R(t) are the failure density and reliability function respectively.

Failure rate or Hazard rate

The rate at which a failure will occur in a certain interval of time (t1 and t2) is defined as the **failure rate** during that interval. It is defined as the probability of a failure per unit time, given that the failure has not occurred prior to time point V, the beginning of the interval.

Therefore, the failure rate is given by the following formula:

$$Failure\ Rate = \frac{[R(t1) - R(t2)]}{[(t2 - t1)R(t1)]}$$

The preceding expression in the interval (t, t + dt) and can be written in the following way:

$$Failure\ Rate = \frac{[R(t) - R(t + dt)]}{[R(t)dt]}$$

Hazard function [h(t)]

The **hazard function [h (t)]** is defined as the limiting value of the failure rate when the length of Interval approaches zero. Therefore, hazard function is defined as the instantaneous failure rate.

$$h(t) = \lim_{dt \to 0} \frac{[R(t) - R(t + dt)]}{[R(t)dt]}$$

$$h(t) = \frac{F(t)}{R(t)}$$

Therefore, h(t) dt is the probability that a component of age 't' fails in the interval of time (t, t + dt).

Failure density function [f(t)]

Failure density function can be expressed in terms of hazard function and reliability function. The hazard function and reliability function are related to each other. The hazard function can be rewritten as follows:

$$h(t) = \frac{d}{dt}[\frac{1 - R(t)}{R(t)}]$$

Therefore, the failure density function f(t) is defined as follows:

$$f(t) = h(t).\exp\left[\oint_0^t h(t).dt\right]$$

Problem statement 1

Consider a case of closed chamber humidity sensing device. What was the failure rate of individual parts, if the base failure rate is given as 0.033 failures per hour, stress factor (environment) is 0.92, and quality factor is 0.98?

Solution:

The failure rate of the closed chamber can be calculated as follows:

$$Failure\ rate = Base\ failure\ rate \times quality\ factor \times environmental\ stress\ factor$$

$$FR = \lambda b \times \pi q \times \pi e$$

$$FR = 0.033 \times 0.98 \times 0.92$$

$$FR = 0.30\ failure\ per\ hour$$

Configuration in the context of reliability analysis

The reliability factor or the probability of failure of the system is to be determined, but it is very difficult to analyse such a system in its entirety. In practice, the system is decomposing it into subsystems or units and elements, whose individual reliability factors can be estimated. These subsystems and elements are connected to constitute the given system, the combinatorial rules of probability are applied to obtain the system reliability. Some of the configurations that are discussed in the theory of reliability are as follows:

Series configuration

Parallel configuration

Mixed configuration

The configuration and related reliability expressions are expressed as follows:

Series configuration

Series configuration is the simplest one, and is identified as mostly a common design in reliability analysis. In the series system, the functional operation of the system depends on the proper operation of all components in the system, and only one component needs to fail for the entire system to fail. The system consists of units which are connected in series, as seen in the following screenshot:

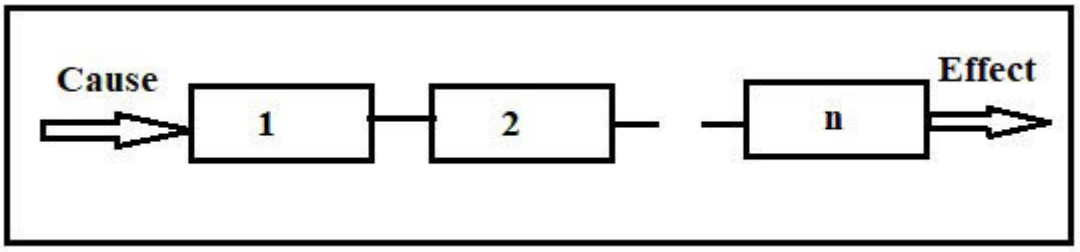


Figure 1.1: *Reliability Block Diagram – Series System*

If the system consists of 'n' units (all connected in series), the reliability of the series system is given by the following formula:

$$Rs\ (t) = p(s)$$

$$Rs\ (t) = p(x1).p\left(\frac{x2}{x1}\right) \ldots . p(\frac{xn}{x1}\ and\ x2\ and \ldots . and\ x(n-1))$$

Here, the components are dependents.

If the 'n' units are independent, then the expression for the probability of successful operation is as follows:

$$Rs\ (t) = p(s) = p(x1).p(x2).p(x3)\ldots.p(x(n))$$

If the units are identical then the expression for the probability of successful operation is as follows:

$$Rs\ (t) = [R(t)^n]$$

If time to failure follows exponential distribution, then the reliability of series system with 'n' units is as follows:

$$Rs\ (t) = \exp\left[-\sum_{i=1}^{n} \lambda i(t)\right.$$

The mean time to failure of the system in terms of the reliability function is given as follows:

$$MTTF = \int_0^{\infty} R(t)\ dt$$

$$MTTF = \frac{1}{-\sum_{i=1}^{n} \lambda i}$$

Problem statement 2

If three individual systems 'A', 'B', and 'C' are connected in series, with a reliability of 0.9, calculate the reliability of the complete system 'F'.

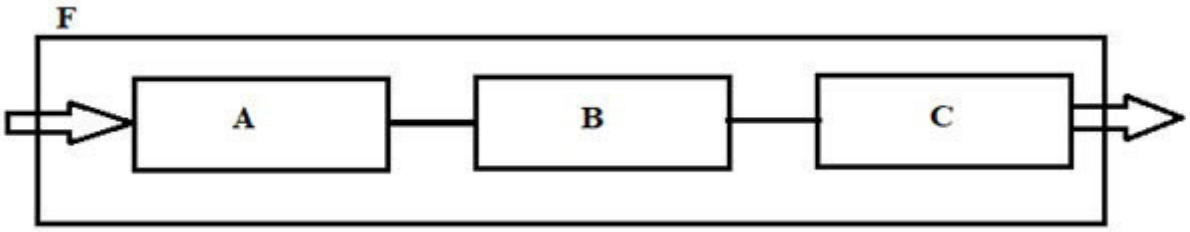


Figure 1.2: *Series connected system*

Solution:

The reliability of system 'A' is: 0.9

The reliability of system 'B' is: 0.9

The reliability of system 'C' is: 0.9

Reliability of complete system can be calculated as follows:

$$Rc = (Ri)^3$$

$$Rc = (0.9)^3 = 0.729$$

Problem statement 3

In a system 'F', there are four components 'A', 'B', 'C', and 'D', which are exponentially distributed. The failure rates of 'A', 'B', 'C', and 'D' are 0.002, 0.002, 0.001, and 0.003. Formulate an

expression for the reliability and explore the reliability of system 'F' at 100 hours' time period.

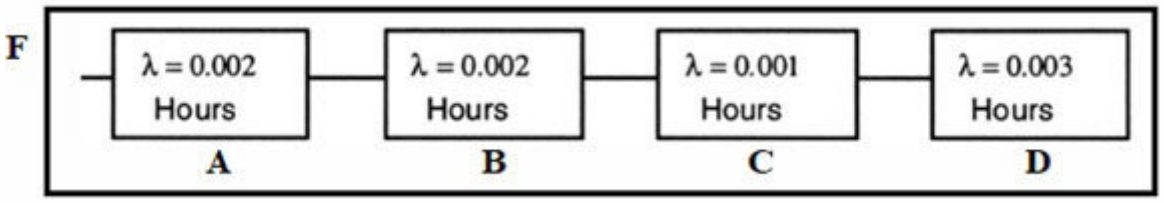


Figure 1.3: *Exponentially distributed system*

Solution:

The reliability for the exponential distribution is as follows:

$$R(t) = e^{-\lambda t}$$

The reliability of system 'F' is as follows:

$$Rf(t) = (e^{-0.002t}) \times (e^{-0.002t}) \times (e^{-0.001t}) \times (e^{-0.003t})$$

$$Rf(t) = e^{-0.008t}$$

The hazard function λ is as follows:

$$\lambda s = 0.002 + 0.002 + 0.001 + 0.003$$

$$\lambda s = 0.008$$

At time period 100 hours, reliability of the system 'F' is as follows:

$$Rf\ at\ t = 100 hours = \ e^{-0.008\,(100)} = 0.4493$$

Parallel configuration

Several systems exist in which successful operation depends on the satisfactory functioning of any one of their n sub-systems or elements. These are connected to be in parallel. The block diagram representing a parallel configuration is shown in the following screenshot:

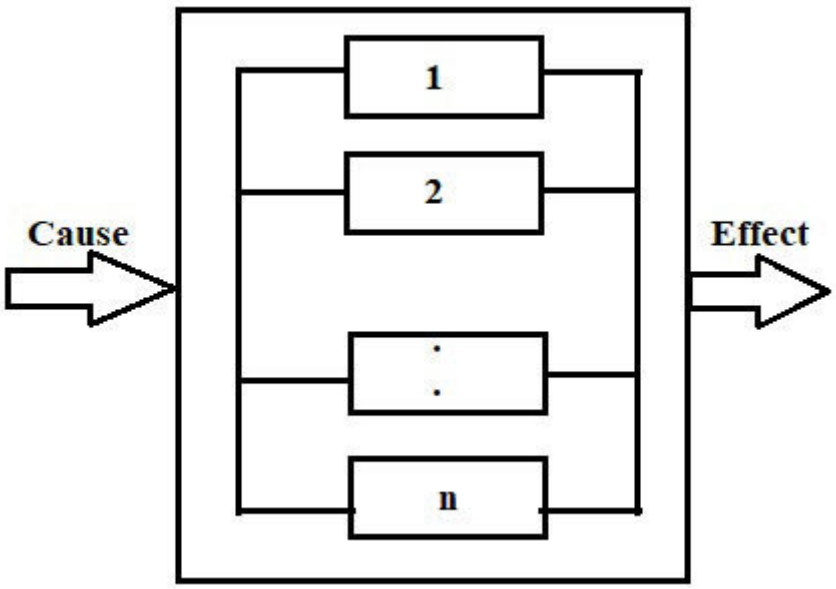


Figure 1.4: *Reliability block diagram – parallel configuration*

For a system with 'n' units connected in parallel, the reliability of the system is given as follows:

$$Rs\ (t) = p(s) = 1 - [P(\overline{x1}).P\left(\frac{\overline{x2}}{\overline{x1}}\right)...P\frac{\overline{xn}}{\overline{x1}}\ and\ \overline{x2}\ and\ .....and\ \bar{x}(n-1)]$$

If the elements are independent and also identical, then system reliability is given by the following formula:

$$Rs\ (t) = p(s) = 1 - [1 - \exp\ (-\lambda i\ (t))^{n}]$$

If the units in the system are constant and identical, then mean time to failure is as follows:

$$MTTF = \int_{0}^{\infty} Rs\ (t)dt\ = \frac{1}{\lambda}\sum_{i=1}^{n}\frac{1}{i}$$

Mixed configuration

In this mixed one, there are two types of configurations – one is series-parallel configuration and the other is parallel-series configuration.

Series-parallel configuration

The block diagram representing a **series-parallel configuration** is seen in the following screenshot:

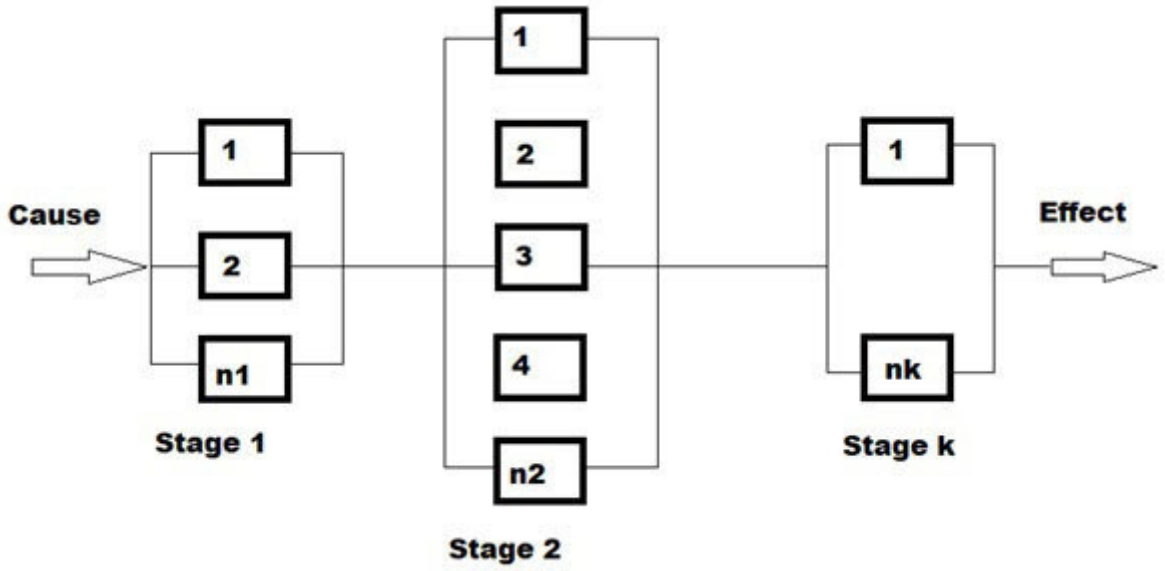


Figure 1.5: *A block diagram for series-parallel configuration*

The reliability of the system for series-parallel configuration is given by the following formula:

$$Rs = R1.R2.R3 \ldots \ldots .Rk$$

$$= \prod_{i=1}^{k} \{1 - \prod_{j=1}^{n} [1 - p(xij)]\}$$

Parallel-series configuration

The block diagram is drawn for **parallel-series** and is shown in the following screenshot:

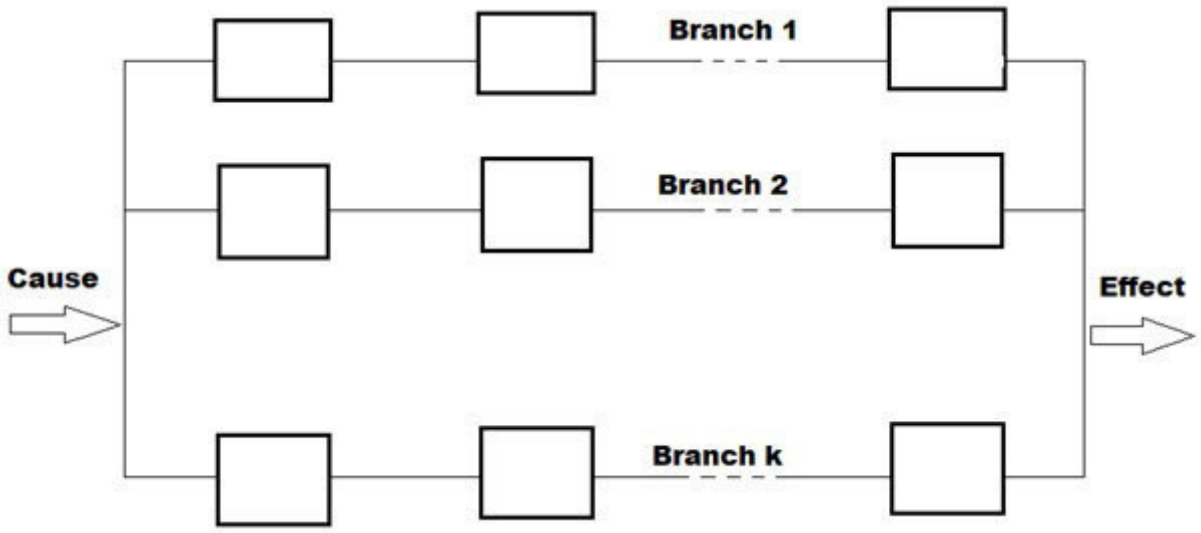


Figure 1.6: *The block diagram for Parallel-Series configuration*

For the parallel-series configuration, the system reliability is as follows:

$$Rs = 1 - \prod_{i=1}^{k} [1 - \prod_{j=1}^{n} p(xij)]$$

Problem statement 4

A home computer has two 3.5-inch disk drives. These disk drives are parallelly connected with other computer devices such as hard drive, CPU, keyboard, and monitor, as per the following arrangement:

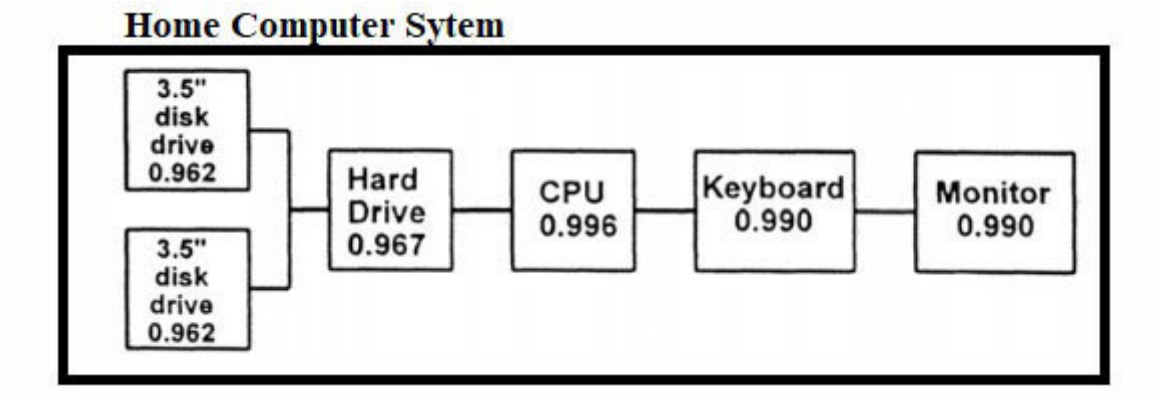


Figure 1.7: *Home computer system*

Explore the probability at 1000 hours, assuming reliability components as follows:

follows:
follows:
follows:
follows:
follows:
follows:

Table 1.1: *Reliability components*

Solution:

The home computers system has parallel-series connection of devices. First, we will calculate the reliability of parallel system:

$$R\ (Disk\ drives) = 1 - (1 - 0.962) \times (1 - 0.962)$$
$$R\ (Disk\ drives) = 0.9986$$

The reduced parallel-series model is shown in the following screenshot:

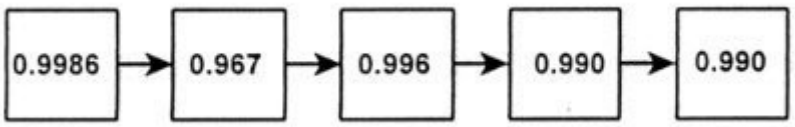


Figure 1.8: *Reduced parallel-series model*

The reliability of the home computer system at 1000 time period is as follows:

$$Rs = 0.998 \times 0.967 \times 0.996 \times 0.990 \times 0.990$$
$$Rs = 0.9426$$

Problem statement 5

In a school premises, there are two practical labs. In each practical lab, there is one computer each. In the first lab, the computer operates continuously and MTTF is 200 hours. This

MTTF has exponential distribution. In the second lab, an identical computer is placed, and it has also reported some MTTF while the computer is in standby mode, which is 1000 hours. This MTTF for the second lab is also exponentially distributed.

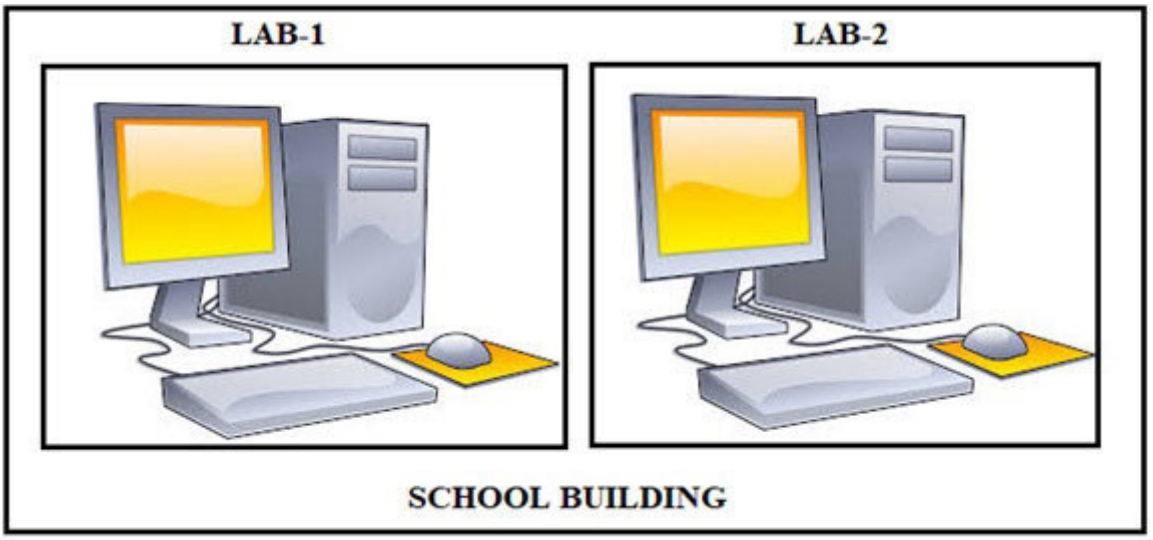


Figure 1.9: *Integrated labs in a school building*

Find out the following:

Mean time to Fail (MTTF) for the school labs

Reliability at 300 hours

Solution:

In case of failure of a component while it is in standby mode:

Mean time to Fail (MTTF) for the school labs is as follows:

$$MTTF = \frac{1}{0.005} + \frac{1}{0.001} - \left(\frac{0.005}{0.001}\right)\left(\frac{1}{0.005 + 0.001}\right)$$

$$MTTF = 366.7$$

Reliability at 300 hours is as follows:

$$MTTF = \frac{1}{0.005} + \frac{1}{0.001} - \left(\frac{0.005}{0.001}\right)\left(\frac{1}{0.005 + 0.001}\right)$$

$$MTTF = 366.7$$

Reliability analysis of Wireless Sensor Networks

Using low cost, inexpensive, and untethered wireless sensor nodes, the purpose of sensing parameters and events over a region has dramatically removed the constraints associated with traditional wired methodologies, thus providing a paradigm shift in the approach towards the process of data acquisition. These nodes can be left unattended for long period of time, and they have the ability to self-organize to form a network, and ensure delivery of sensed information or event to each other for collaborative sensing, besides sending the information to a centralized data warehouse.

Wireless Sensor Networks and data acquisition systems

A key difference between the usage of Wireless Sensor Networks and the traditional data acquisition systems lies in the fact that the traditional systems focus on the accuracy of the sensed information at a specific point, while in the case of Wireless Sensor Networks, the focus is not on the degree of accuracy of the reading, but more on what can be inferred, at a remote location, by using a bunch of readings obtained from various low cost, low reliability sensor nodes measuring similar data in a given region.

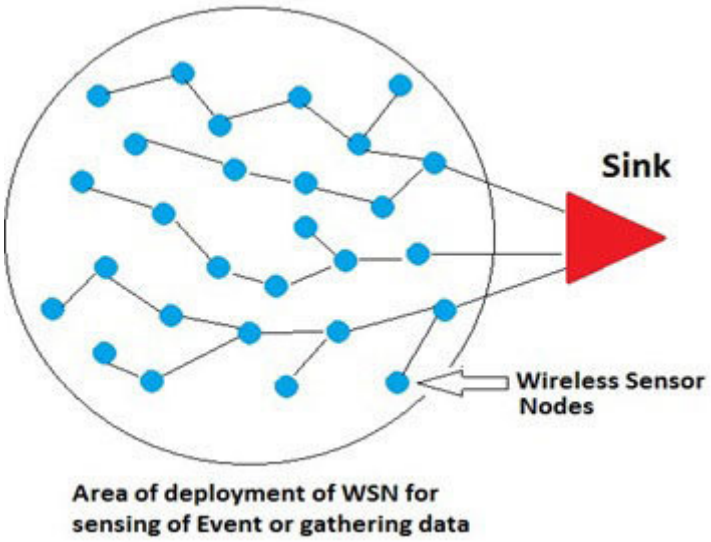


Figure 1.10: *Wireless Sensor Networks (WSN)*

Therefore, having highly accurate and reliable sensors on-board the sensor nodes is not a key requirement in the Wireless Sensor

nodes. This difference can be explained with the help of the following example.

If the requirement is to measure the rate of flow of water passing through a pipe for the purpose of billing, then a single point reading made by a high accuracy sensor mounted on the pipe would be the correct methodology. However, if the requirement is to identify whether the soil in a large field is dry, slightly moist, or very moist, then one high accuracy sensor would not suffice. Having a large number of high accuracy sensors could be a possible solution to this problem; however, the solution would be very expensive and probably give much higher accuracy than what is needed, since the original requirement was to only identify regions with dry, slightly moist, or very moist soil.

The solution of this problem could be met with reasonable reliability by deploying large number of low costs, low accuracy sensor nodes spread over the region, and infer the moistness of soil in the various parts of the field by studying the data obtained from these sensors. Thus, utilizing Wireless Sensor Network in this problem could actually be a more reasonable and realistic solution.

The solution could be upgraded by introducing Actuator Nodes in the network, which could then control the amount of irrigation in specific regions based on the inferred information. However, the requirements in that scenario will be more stringent.

Constraints of Wireless Sensor Networks

The various constraints faced by a typical Wireless Sensor Network include the following:

The Wireless Sensor Nodes are battery operated, have short-range radios on board along with low cost low accuracy sensors, are small sized, and have low computing and memory resources. Thus, these nodes are energy constrained, have low computational capability, low accuracy of sensing, and are prone to hardware and communication failure.

Since the nodes may be deployed in areas where they are exposed to harsh vagaries of the environment, including exposure to extreme temperatures, humidity, and other such physical factors, the probability of a node failure is high.

The wireless medium itself is prone to irregular and unpredictable behaviour because of issues like interference and channel fading.

Moreover, since the same medium is being used for communication by all the nodes in a network, the probability of loss of information because of packet loss and network congestion is high.

Methods for Wireless Sensor Networks

The standard methods adopted by Wireless Sensor Networks to get over these constraints are as follows:

Redundancy is introduced in the network by deploying significantly larger number of sensor nodes than what are actually needed for sensing and eventual reliable estimation and re-construction of the sensed event at the sink. This is done to counter the issue of node failure and packet loss during communication, since with a larger number of nodes participating, the probability of sufficient number of nodes remaining un-affected by the node and communication failure for reliable re-construction and estimation of the event sensed in the region of deployment is high.

The adverse impact on the Network life-time because of energy constraint on the nodes is offset to an extent by making the nodes go into low power sleep mode when not sensing, thus conserving battery life. Mechanism is also introduced to ensure even loading of the nodes in a network, so that the overall network life time improves.

Evolution of Wireless Sensor and Actuator networks

Over time, the Wireless Sensor Networks have evolved into Wireless Sensor and Actuator Networks (WSAN), which consists of special nodes called **Actuator nodes** besides the typical Wireless Sensor Nodes. The Wireless Sensor Nodes perform the task of gathering information about the environment in which they are deployed. Additionally, special nodes called Actuator nodes are also introduced into the network and have the ability to actuate upon some control elements that have an impact on the environment in which the sensor nodes are deployed. Actuator Nodes are not energy constrained, have higher computational and memory capabilities, better communication capabilities, and are able to actuate upon some controllable element. With the introduction of Actuator Nodes into the network, the following two network architecture, as shown in the following screenshot, are generally observed:

Centralized Decision Making (Semi-Automated)

Distributed Decision Making (Automated)

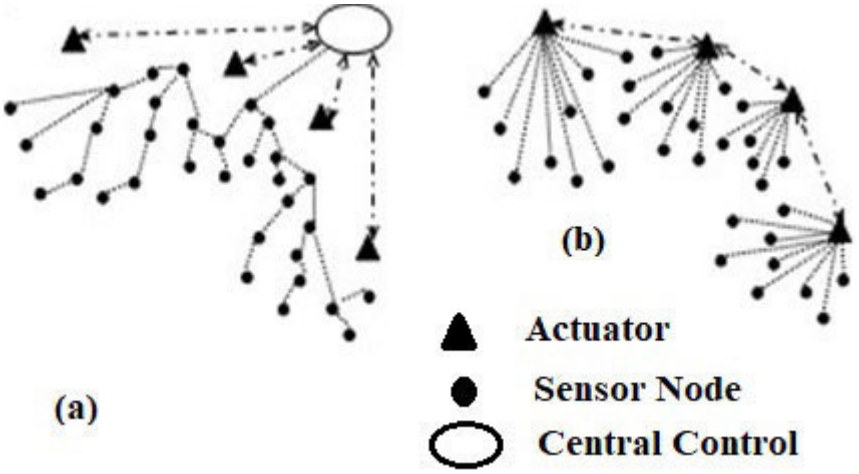


Figure 1.11: *a) Centralized Decision-Making Architecture, and b) Distributed Decision-Making Architecture*

Centralized decision-making architecture

In the case of **centralized decision-making** approach, the sensor nodes pass on the sensed information to a centralized sink, where the decision on the control action to be taken by the multiple actuators is decided based on the gathered information. This information is subsequently passed on to the actuators for implementation by the actuators.

Distributed decision-making architecture

In the case of **distributed decision-making** approach, the sensor nodes send the gathered information to specific actuators, who then communicate and collaborate among themselves to take decision about the specific control action to be performed by each one of them. The second approach is more in tune with the actual definition of Wireless Sensor Networks, where the issue of collaborative deduction of an event and the response to it is highlighted. Wireless Sensor and Actuator Networks are expected to significantly accelerate the acceptability of Wireless Data Acquisition and Control systems in applications which are non-real time and do not employ very complex control action.

However, with the evolution of Wireless Sensor and Actuator Networks additional constraints, scientists have been thrust upon the reliability of the data acquisition process of the network, since the decisions taken for control of actuating action depend upon the data acquired by the sensor network. These are as follows:

Since the Actuator Node/s are required to take a decision on implementation of the control action, based on the estimation or re-construction of the event relying on information delivered by the sensor Nodes, it is imperative that the control action is time coherent with the circumstances of the environment. This means that the delay between the time an event is sensed by the deployed nodes and the time when the action is taken by the

actuators must be as less as feasible to ensure that the control action is not delayed.

Thus, an additional constraint is placed on the **Network Latency Time** which becomes critical in the case of WSAN, i.e., the time lag between detection of event by a sensor node and the time the same is reported at the sink /actuator, TNLT, must be less than the desired Actuation Latency Time of the application.

Modes of Data Acquisition

The prime purpose of deployment of a WSN is to gather information about the environment in which it is deployed, and then pass on the collected information to the sink, which may be located remotely. The collected information is then assessed to estimate or re-construct the events occurring in the deployment area. The deployed nodes generally scan and collect information periodically but will send the gathered information to the sink depending upon the mode of Data Acquisition, which could be one of the following:

Periodic Data In this mode, the nodes will not only collect the information periodically, but will also transmit the collected information periodically to the sink. The frequency of data sampling would generally be much higher than the rate at which the collected information is transmitted to the sink. This is because the energy spent by the node on sensing and computing is generally significantly less than the energy spent in transmitting the information, although there are certain applications where the reverse has been found to be true.

Event Based Data In this mode, the deployed nodes may scan and collect information periodically; however, they will transmit the information only when a specific pre-defined event occurs. The network life in this mode tends to be significantly higher as

compared to Periodic Data Acquisition mode, since the nodes will not transmit periodically, thus saving considerable amount of energy. This mode is not suitable for applications where periodic updates about the event area are needed, e.g., habitat monitoring.

Query Based Data In this mode, the deployed nodes may scan and collect information periodically; however, they will transmit the information only when they are specifically queried about the information. In this mode, the sink will initiate a query which will be propagated throughout the network, also known as interest propagation. Only those nodes which fulfil the criterion of the query will send the information available with them. One of the critical aspects of this mode is that the query needs to be propagated to all nodes in minimum amount of time, and with consumption of least amount of energy.

Hybrid Data This mode is a combination of the previously mentioned modes. Different sections of the deployed nodes may be using one or more of the previously mentioned data acquisition modes.

Generally speaking, the event based data acquisition mechanism will use the least amount of energy, followed by query-based, and then subsequently periodic-data acquisition.

Reliable Data Acquisition

The concept of reliability of data acquisition has been defined in different contexts as discovered during the literature survey. The traditional definition of reliability of a system, as mentioned in the theory of reliability is as follows:

$$Reliability(t) = e^{-\lambda t}$$

Here, λ is the failure rate.

This definition indicates that for a given system under observation, if the failure rate is constant, then the reliability of the system will reduce with time in an exponential manner. Here, the constant failure rate means the average failure rate observed over a period of time.

The **traditional definition** is valid in context of a Wireless Sensor Network, even though Wireless Sensor Network is a virtual entity composed of widely distributed physical sub-entities called Sensor Nodes. These nodes are not physically joined to each other; however, they are able to communicate and share information among themselves to collaboratively perform the task of sensing or detecting in the environment where they are deployed, and thus act as a system.

In a Wireless Sensor Network, this definition of reliability can be observed in different contexts, as mentioned in the following screenshot:

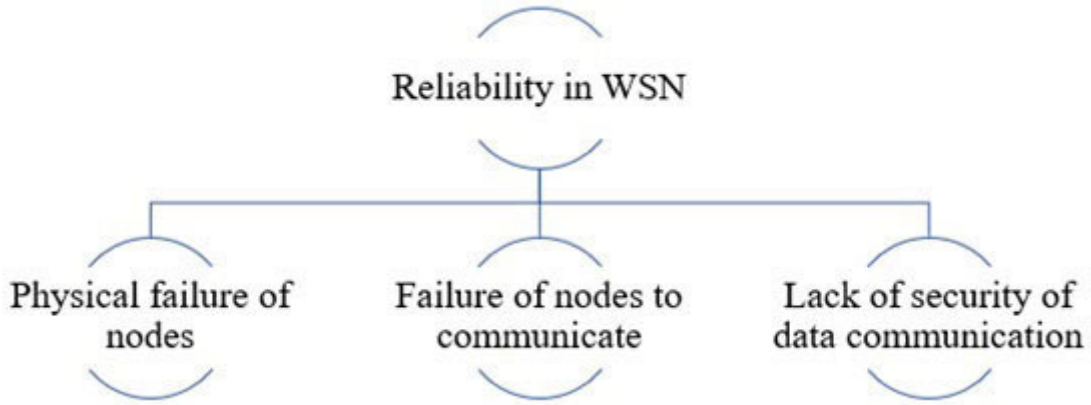


Figure 1.12: *Reliability context in WSN*

In context of physical failure of nodes:

If the rate of failure of nodes in a Wireless Sensor Network is constant, due to physical damage or draining out of the battery, then the reliability of the network to perform the assigned task of collecting information or detecting events in the environment of deployment, will decline exponentially with time. The validity of this statement is easily verified, since it is clear that as the nodes in a network die, the ability of the network to acquire information about the environment, in which it is deployed, drops significantly, since the number of sensing points reduce and the probability of missing out on the detection of an event increases. Thus, the Reliability of Coverage (or Sensing) will reduce exponentially as more nodes keep on failing on a regular basis.

In context of failure of nodes to communicate:

The medium of communication in a WSN is highly un-predictive and its characteristics and behaviour change constantly. This has an obvious impact on the ability of the nodes to communicate with each other and share the information collected, which is an issue at the core of the existence of the Wireless Sensor Network. As more and more nodes fail to communicate with each other, the ability of the network to pass on the acquired information to the sink reduces thus. This lack of ability to pass on the information collected by the nodes to the sink is reflected in a parameter called Packet Delivery Ratio [95], which is measured as follows:

$$Packet\ Delivery\ Ratio = \frac{\text{Total Number of Packets received at Sink}}{\text{Total number of Packets sent by the nodes}}$$

As the Packet Delivery Ratio of a Wireless Sensor Network drops constantly, the Reliability of Delivery of sensed information degrades exponentially.

In context of lack of security of data communication among nodes:

As the nodes are using the wireless medium for communication among them, the information transmitted by them in an open medium leaves the possibility of the transmitted information being intercepted by unauthorised or rouge nodes, which may ingratiate themselves into the network. This could have an adverse impact

on the performance of the network as the information could be misused.

Further, these rogue nodes may start feeding false information to the nodes or may even take control of the nodes within the network. If more and more nodes in the WSN get compromised, then the Reliability of Secure Data Exchange in the network will degrade exponentially.

As can be seen, the definition of reliability could have different connotation in a Wireless Sensor Network.

Another important parameter defined in the traditional theory of reliability is Availability of the system, which is defined as follows:

$$Availability = \frac{\text{MTBF}}{\text{MTBF+MTTR}}$$

Here, MTBF is Mean Time Between Failures and MTTR is Mean Time To Repair.

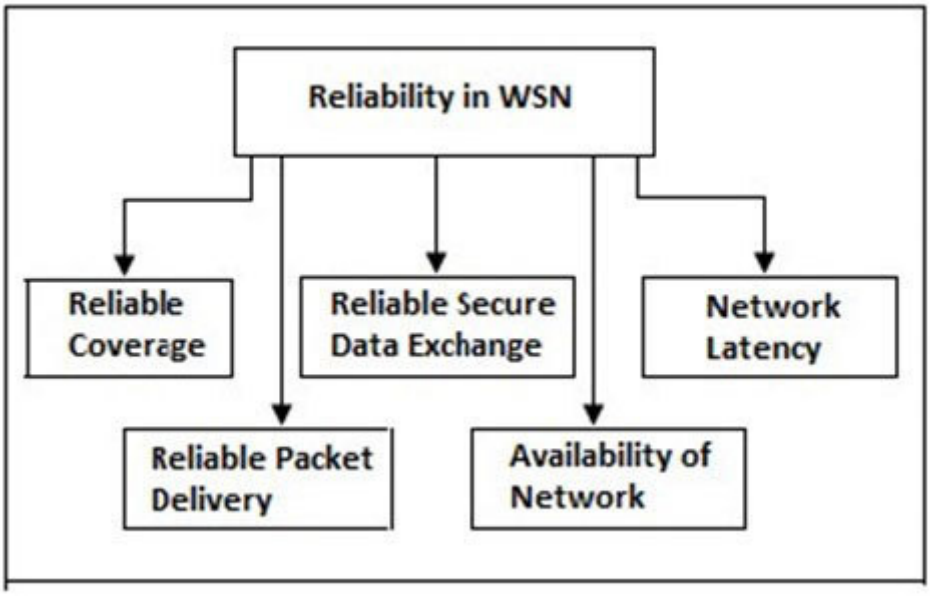


Figure 1.13: *Categorization and Definition of Reliability*

This parameter, also known as **Operational** is an indicator of the overall reliability of the system, as it indicates the probability that the system will be available to perform the assigned task at any given time.

In context of Wireless Sensor Networks, availability may be seen in context with the service that the WSN is expected to provide, that is, sensing information or detecting a specific event, and then ensuring that the information gathered is successfully passed on to the sink, where subsequent action pertaining to the gathered information can be taken.

If the WSN is unable to provide satisfactorily the task of gathering and passing on the information, then the network could be called as being un-available, or it could be stated that the Availability of the network is low.

The non-availability of a network can be primarily because of the fact that large number of sensor nodes comprising the network may have failed due to physical failure or draining out of their battery. Thus, a network with long Network Lifetime would have higher Availability as compared to a network with low network lifetime. The non-availability of the network could also be attributed to lack of ability of the WSN to deliver satisfactorily the service that it is expected to provide.

Thus, if a Wireless Sensor Network is able to provide Reliable and satisfactory service, despite failure of some sensor nodes, the availability of the Wireless Sensor Network will be high. Within the Wireless Sensor Network, on a micro-level, Availability could also be construed as the availability of a neighbour of a sensor node for forwarding the information gathered towards the sink.

Specific form of reliability required may change from application to application. Since the primary reason for deploying a Wireless Sensor Network is to sense information or detect event within the deployment zone remotely, and then be able to pass on this information to the sink for estimation and reconstruction at the sink, the Sink Reliability of Data Acquisition then becomes an important parameter which encompasses the various definitions of reliability and availability associated with a Wireless Sensor Network.

From the perspective of the Sink, Reliable Data Acquisition could be defined as the ability of the Wireless Sensor Network to ensure delivery of sufficient amount of the gathered information by the

deployed sensor nodes to the sink, for it to be able to faithfully and successfully re-construct the event sensed and detected by the nodes.

This will further include the availability of the data acquisition service being provided by the network, for as long as possible without compromising on the ability of the centralized sink to faithfully re-construct the event sensed by it. Reliability also includes the ability of the network to be tolerant to faults, within a limit, without compromising on the basic issue as mentioned earlier.

Issues in reliable data acquisition

There are a few issues which are different in the case of a WSAN, and which have an impact on the definition of Reliable Data Acquisition. In the case of a Wireless Sensor and Actuator Network, the possibility of Distributed Decision making also exists, which requires that the data sensed by the deployed nodes should be sent to the closest Actuator rather than a centralized sink, therefore mechanism for this to happen reliably must exist.

Further in the case of a WSAN, there is a time constraint on the **Network Latency Time** that is, the time difference between the sensing of information by the deployed node and the time at which the sensed information is received at the Centralized sink or the Actuator. This time constraint, although application specific, exists to ensure that the action taken by the actuators is in coherence with the sensing done by the deployed nodes, and the control action is not erratic and un-stable.

Therefore, in context of a Wireless Sensor and Actuator Network, Reliable Data acquisition refers to the ability of the Wireless Sensor and Actuator Network to ensure delivery of sufficient amount of the gathered information by the deployed sensor nodes, in a time-bound and coherent manner to the centralized sink for it to be able to faithfully and successfully re-construct the event, and take necessary action in time.

Coherent manner indicates that the sequence of delivery of data at the sink/actuator is in the same sequence in which the data is generated at the sensor nodes, that is, the sequence in which the nodes detect the occurrence of the event. Reliability further includes the availability of the data acquisition service being provided by the network for as long as possible, without compromising on the ability of the centralized sink to faithfully reconstruct the event sensed by it. Reliability also includes the ability of the network to be tolerant to faults, within a limit, without compromising on the basic issue as mentioned earlier.

Application areas of reliability

Reliability has the vast area of applications starting from small toy to satellite. The application area of reliability is as follows:

Mechanical reliability

Software reliability

Electronics reliability

Structural reliability

Robot reliability and safety

Power system reliability

Mechanical reliability includes critical health assessment of mechanical components such as shafts, bearings, gear, and sliders, etc. The software reliability targets failure-free software operation for a specified time period. The structural reliability is concerned with the reliability of engineering structures, in particular civil engineering, whereas robotics reliability assures the successful operation of robots in confined environment.

Conclusion

This chapter highlights the need of reliability in the electrical and electronic systems for the successful operation under various conditions of environment and electrical parameters. Different types of evaluation parameters of reliability analysis are discussed in this chapter. The application area of reliability is highlighted in this chapter, along with the basic reliability issues such as data acquisition and data prediction etc.

In next chapter, the various methods Markov model, Weibull distribution and so on, are discussed.

Questions

What is the difference between failure and fault? Elaborate the concept using examples.

In home automation system, there are four electrical appliances that are connected in series. It is assumed that if more than one appliance fails, the complete system will shut down. Assume that the failure rate of all the electrical appliances is 0.000414.

Find out the following:

At time period 400, what is the value of reliability of home automation system?

Calculate the 'mean time to fail' for the complete home automation system.

If four individual systems 'A', 'B', 'C', and 'D' are connected in series, with a reliability of 0.61, calculate the reliability of the complete system 'F'.

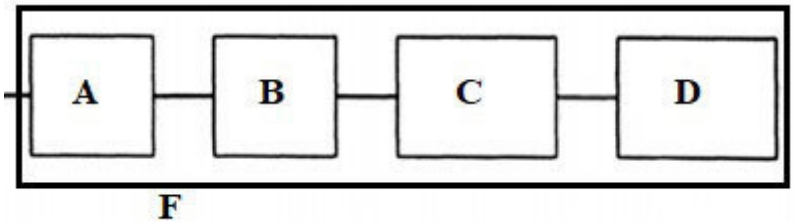


Figure 1.14: *Series connected model*

What do you understand by the following terms:

MTBF

MTTF

MTTR

FIT

Reliability

What is the difference between reliability, availability, and validity?

What is the role of reliability in wireless sensor networks? How will you differentiate between Centralized Decision-Making Architecture and Distributed Decision-Making Architecture?

In an electronic gadget, five transistors 'A', 'B', 'C', 'D', and 'E' are connected in parallel. All the transistors are having reliability of 0.70 individually.

Calculate the reliability of the entire electronic gadget.

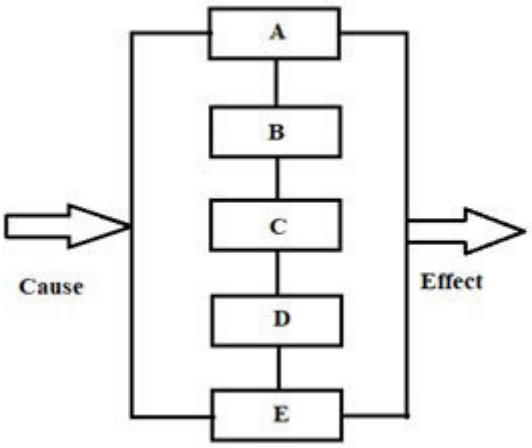


Figure 1.15: *Parallel connected model*

In a closed chamber, there are eight individual components, ranging from A to H. Out of which 'A', 'B', 'C', 'D', and 'E' are parallelly connected and 'F', 'G', and 'H' are connected in series.

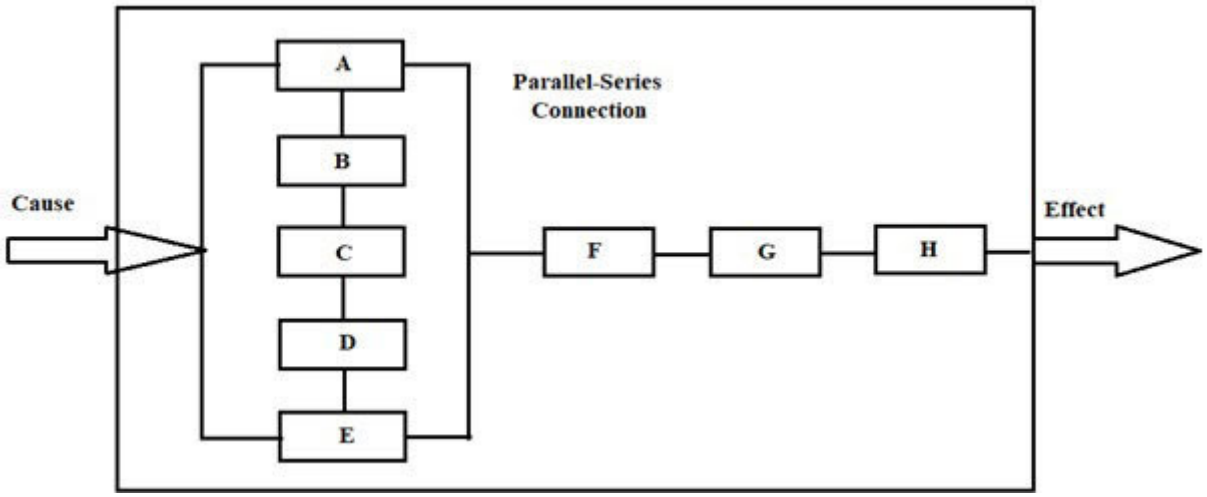


Figure 1.16: *Closed chamber*

The reliability of all components is as follows:

follows:

follows:
follows:
follows:
follows:
follows:
follows:
follows:
follows:

Table 1.2: *Reliability of all components*

Find out the reliability of the complete closed chamber.

What is the relation between MTBF and FIT in terms of reliability?

Reliability prediction can reduce the problem of e-waste to a great extent. Justify this statement using live examples.

CHAPTER 2

Reliability Measures

Introduction

Nowadays, all the industries are making use of more and more automation in production. It results in the complexity of the industrial system, and therefore, requires special attention in the fault-free operation of the system as the failure of any component will definitely stop the working of the system. Many approaches have been used for improving the operation of a system, such as understanding of failure, improved manufacturing techniques, careful planning, design and so on, so that the reliability of a system is achieved.

Structure

In this chapter, we will discuss the following topics:

Reliability, availability, validity, and maintainability

Reliability measures

Need of reliability analysis

Electronic component failure modes and mechanism

Objectives

After studying this chapter, the students should be able to understand the concepts of reliability, availability, and maintainability. The reliability evaluation parameters are highlighted for the condition monitoring of components, devices, and gadgets. The various failure modes, techniques, and mechanism of electronic components are further elaborated with the help of suitable applications and examples.

Introduction

In the modern era, systems and devices are operating under many environmental and operating conditions. These conditions affect the working of the components of the systems. Many times, the failure of the systems plays a crucial role. There are many systems where the failure of the components or devices plays an important role, such as failure in power plant, satellite communication, network system, telecommunication system, and so on. There are many other cases that affect the daily life of human beings, such as failure of different electronics home equipment.

Reliability engineering is the branch of statistics and engineering. Reliability engineering covers both qualitative and quantitative part. Reliability measurements are indispensible for any system, but it cannot make a system reliable. However, the reliable design of the system can achieve the reliability target.

Reliability analysis is also an important tool for failure free operation of other engineering systems such as power plant system, networking systems, etc. With the help of reliability analysis, we can identify the critical components of the various engineering systems.

A satellite communication system provides a link between transmitter and receiver. There are many uses of satellite communication system, such as in broadcasting, internet, and military operations, etc. Cost effectiveness, availability, and multi-point communications are the main advantages of satellite communication. Many subsystems are affected by the failure of the satellite. So reliability analysis is very important for satellite communication system. With the reliability analysis, we can identify the availability, sensitivity, and the failure-free operation of the system.

In adeveloping or developed country, a telephone is the essential part of life. The voice communication in local, national, or international is connected with public switched telecommunication network (PSTN). The video conferencing is done by using telecommunication network. The wireless communication is a revolution in a telecommunication network. Financial transactions, radio communication, etc., are affected by the failure of the telecommunication system.

Definition and scope of reliability

The words reliable and unreliable areused for dependable and undependable of the system. The reliable system means failure free operation of the system in a given period of time. Reliability affects every device, ranging from small transistors to different components of satellite communication system. The main aim of reliability is to increase the ability of a system under given operating conditions. The reliability of a system is affected by many constraints, such as cost factor, economic benefit, operating conditions, etc. Different optimization techniques have also been applied in designing the reliable system. Reliability is necessary for a successful operation of a system.

Generally, the word reliability means dependability or repeatability. Reliability of a system is a probability of failure-free operation of a system in a given specified period of time. Suppose, a person buys an LED bulb and the shopkeeper gives him a 3-year warranty on a particular brand, which means this particular brand of LED will provide light for 3 years without giving any trouble.

Since reliability is a probability, therefore, its numerical value lies in between 0 and 1. If the reliability of a system is 1, thent he system is operable 100 percent failure-free.

Reliability of a system at any time 't' can be defined as the ratio of a number of holdovers at any time 't' to the initial total

numbers of holdovers.

Reliability is also defined as the science of predicting, analysing, preventing, and mitigating failures over time.

The main definition of reliability is as follows:

Reliability *is the probability of a device performing its purpose adequately for the period intended under the given operating conditions.* This definition of reliability covers the 4 main factors, as shown in the following screenshot:

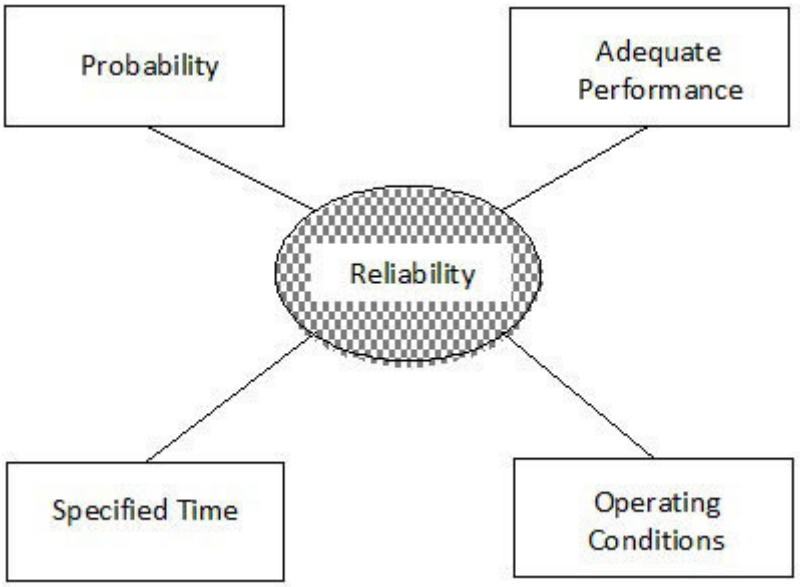


Figure 2.1: *Factors of reliability*

Probability

Probability may be defined as the chance of occurrence of an event. Probability is the ratio of favorable outcomes and total possible outcomes. The value of probability lies in between 0 and 1. If the probability is zero, then the event is called an impossible event, and if the probability is 1, then the event is called a sure event. Suppose the probability of hitting a target is 0.3, this means that if a person tries to hit the target 100 times, then the target will be hit 30 times. Therefore, taking another example of reliability as expressed in probability, we can say that if the reliability of the operation of a machine is 0.9, it means the reliability tested under the same condition would be satisfactory only 90 times out of 100.

Adequate performance

It is the second factor of the definition of reliability. The adequate performance means the satisfactory performance of a system. For example, production limits of the machine are 100 to 105 units per hour; to be specific, if we say the production of the machine in the first hour is 104, in the second hour is 105, in the third hour is 104, and so on. This shows the adequate performance of the machine.

Specified time

Specified time is the third factor of the definition of reliability. It represents the period of satisfactory performance of a system. The production of the machine depreciates as the time passes, and at some point of time, the machine fails. The duration of satisfactory performance is also known as the duration of the adequate performance.

Operating conditions

The **operating conditions** or environment represents the working environment of the system in which a machine or system performs adequately. These conditions are like temperature, humidity, etc. It is essential to know the operating conditions, so that the system gives an outstanding performance.

Significance of the operating conditions are as follows:

The operating condition or working environment of the system.

The need of safety sides of men and system.

The degree of uncertainty about the success of the operation and its improvements in system performance.

Need for efficient, economic, and continuous operating system without any disturbances.

A system failure raises the question in the minds of people regarding its reliability and its further use.

Improvement in the confidence of the working personnel, particularly in the hazardous area because of safety reasons.

Reliability measures

The approximation or probability which confines that system is working as per the given set of instructions, and is known as reliability.

Reliability

The reliability of a system is the probability that a system will work properly, that is without any failure for a given period of time under given conditions.

Mathematically, ReliabilityRel(t) is the probability of failure-free operation of the system in the interval 0 to t. If T is the time that a failure occurs in the system, then the system will not fail before time t.

$$Rel(t) = Prob.(T > t)$$

Reliability is a function of time and it is a probability, therefore the value of reliability lies always in between 0 and 1.

$$Rel(0) = 1$$

$$Rel(\infty) = 0$$

The unreliability, F(t) of the system is explained as the probability that a system is failed by the first failure of the component during the time interval 0 to t.

The following relationship holds in reliability and unreliability of the system.

$$Rel(t) + F(t) = 1$$

In other words, the reliability may be calculated as follows,

$$Rel(t) = 1 - F(t)$$

Maintainability

Maintainability is the probability that a failed component is moved on to operable condition in a specified time (down time) when the maintenance is performed under given conditions.
Maintainability is also defined as the probability of down time that a failed component is not in operation due to maintenance.

Availability

Availability is an important characteristic used to calculate the performance of repairable systems. Availability uses properties of both reliability and maintainability. Availability is also a probability that a system is available for a specified period of time (up time). The value of availability lies in between 0 and 1 at any time t.

$$Availability\ (Avl(t)) = \frac{uptime}{uptime + downtime}$$

Availability can be classified into three different types, as shown in the following screenshot:

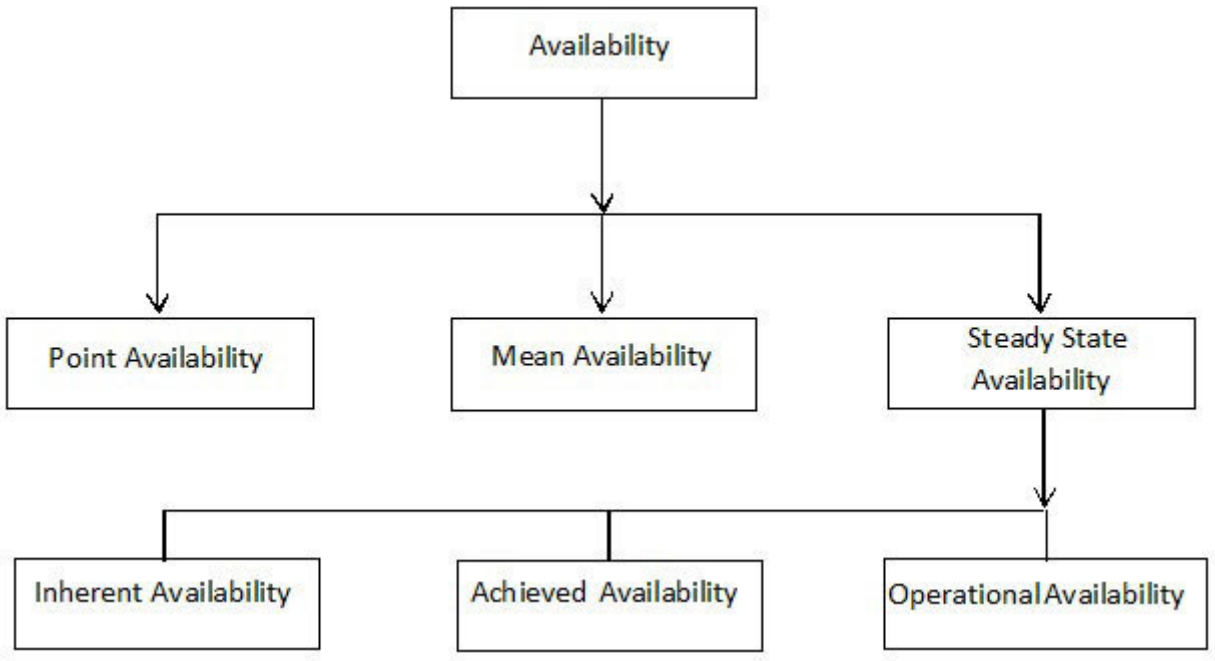


Figure 2.2: *Types of availability*

The various types of availability are point availability, mean availability, and steady-state availability.

Point availability

Point availability is also known as instantaneous availability. Point availability is the probability that a component will be operational at a particular time 't'. Point availability is same as the reliability function of the operable component at time 't'. The component will be operable if one of the following criteria holds:

The component will be operable from time o to t with probabilityRel(t).

The component will be operable properly till the last repair at time γ, $o < \gamma$ with probability, where $f(\gamma)$isthe renewal density function of the component.

So, the point availability is defined as follows:

$$Avl(t) = Rel(t) + \int_0^t Rel(t-\gamma) f(\gamma) d\gamma$$

Mean availability

The proportion of time period that a component is available for operation is known as **mean** Mean availability is also known as average uptime availability. Mean availability represents the average value of instantaneous availability function over the time interval (o, T]. The Mean Availability is explained as follows:

$$\overline{Avl}(T) = \frac{1}{T}\int_0^t Avl(t)dt, 0 < t < T$$

Steady state availability

The **steady state availability** is defined as the limit value of instantaneous availability taking time tends to infinity. It is also known as long run availability. It reveals the long-term availability after the establishment of the system.

$$Avl(\infty) = \lim_{t \to \infty} Avl(t)$$

The steady state availability is further divided into the following three categories:

Inherent availability

Inherent availability is the steady state availability in which we consider the corrective maintenance down time of the system. Inherent availability is the probability that a system will operate properly under given conditions and support the environment without considering any preventive maintenance. The inherent availability can be expressed as follows:

$$Avl(t) = \frac{MTBF}{MTBF + MTTR}$$

Achieved availability

Achieved availability is quite similar to inherent availability. In this availability, we include the preventive maintenance downtime. Achieved availability is the steady state availability in which we consider corrective and preventive downtime of the system.

Achieved availability can be calculated by using the mean time between maintenance action (MTBM) and the mean maintenance downtime (M). It can be expressed asfollows:

$$Avl(T) = \frac{MTBM}{MTBM + M}$$

Operational availability

Operational availability is the real average availability over a period of time. It includes all sources of downtime. Operational availability is the ratio of uptime and total time. Mathematically, it can be expressed as follows:

$$Avl(t) = \frac{uptime}{operating\ cycle}$$

Here, operating cycle represents the overall time period and the uptime is the operating time of the system.

Mean Time to Failure (MTTF)

Mean time to failure (MTTF) is the basic and important index of reliability indices. It is used for non-repairable items. It is the expected mean time or average value of the failures.

$$MTTF = \int_0^\infty Rel(t)dt$$

The Mean Time To Failure (MTTF) can also be obtained by taking Laplace transform of Rel(t):

$$MTTF = \lim_{s \to 0} Rel(s)$$

the Laplace transform

Mean Time to Repair (MTTR)

The time used for repairing of a failure unit, is known as the **Mean Time to** Suppose a hardware part of the system fails, then MTTR is the mean time to repair the part. Nowadays, most of the companies purchase a spare part for replacing the failed part instead of repairing the part.

If the repair time is exponentially distributed with the parameter μ, then the repair density function is defined as follows:

$$f(t) = \mu e^{-\mu t}$$

The mean time to repair time is given as follows:

$$MTTR = \int_0^\infty t f(t)\, dt$$

$$MTTR = \int_0^\infty t\mu e^{-\mu t}\, dt$$

$$MTTR = \frac{1}{\mu}$$

Thus, the MTTR is the reciprocal of repair rate μ. The MTTR is also known as mean down time.

Mean Time Between Failure (MTBF)

Mean time between failures (MTBF) is the basic reliability indices for a repairable system. Mean time between failures is the expected time between two consecutive failures of the system by assuming constant failure rate. In the non-repairable system, the mean time between failures is same as mean time to failure.

If λisthe constant failure rate, then mean time between failures may be defined as follows:

$$MTBF = \frac{1}{\lambda}$$

Thus, the mean time between failures is the reciprocal of constant failure rate λ.

Mean Time Between Maintenance (MTBM)

The maintenance policy is very useful for improving the life time of the system [9]. Mean time between maintenance (MTBM) is another important reliability index. It is calculated when the preventive maintenance is used in the system. If preventive maintenance is equal to zero, then mean time between maintenance is same as the mean time between failures.

If be the availability time period of the system keeping in consideration the preventive maintenance, then mean time between maintenance can be obtained by taking the mean of the precedingtime period.

Mathematically,

$$MTBM = MTBF + Maintenance\ Preventive(MP)$$

Expected profit

The risk is a very important factor to affect any system. If we have the exact information about the failures, then we can decrease the effect of risk and increase the profit. Expected profit is also a very important reliability index. **Expected profit** may be defined as the maximum attainable amount after deducting the overall cost.

If we assume that the service facility is always available, then the expected profit during the time interval (0, t] is defined as [10],

$$E_P(t) = K_1 \int_0^t P_{up}(t)\, dt - K_2.t$$

represents the revenue, is the service cost per unit, and Pup(t) represents the availability of the system.

Sensitivity Analysis

The **sensitivity analysis** is also known as the post optimality analysis. The main goal of the sensitivity analysis is to know how sensitive the solution is to the actual situation. The objective of the sensitivity analysis is to reduce the additional computation efforts which may arise in solving a problem. In many cases, it is not compulsory to solve the problem again, only a small amount of calculations applied to the old solution will be sufficient. Sensitivity analysis is the testing of the system under uncertainty. The extra care is necessary for high sensitive components.

Sensitivity analysis can also be defined as the partial derivative of the function with respect to that factor. These factors are failure rates in the analysis. In reliability theory, we can find the sensitivity of reliability and sensitivity of MTTF. We can find out the sensitivity of reliability and sensitivity of MTTF by differentiating partially the equation of reliability and MTTF withrespect to different failures that occurred in the system.

Systems

The collection of components, subsystems arranged in a specified manner, is known as a A system can be completely or partially failed due to the failure of its components. In other words, the system is the collection of technical or socio-technical components. There are two types of systems in reliability theory.

Repairable systems

Repairable systems are those systems which can be re-established or restored by repairing the failure component of the system without replacing the overall system. The lifetime of the repairable system is the age of the system. The failure rate in the repairable system is the rate of occurrence of failures.

Non-repairable systems

Non-repairable systems are those systems which cannot be re-established or restored by repairing the failure component of the system. It is discarded when the failure occurs. The life time of the non-repairable system is a random variable. The failure rate in the non-repairable system is hazard rate of a life-time distribution.

Failures and Failure modes

A **failure** is the partial or complete loss of the system. Suppose a system is in working mode, but suddenly the system completely or partial fails due to the failure of a component of the system. There is a necessity to identify the main cause of failure of the system for a failure-free operation of the system. Based on the nature of the failure, the failures can be categorized into three different modes. Many a times, a large number of failures occur at an initial stage due to the manufacturing defect of the component of the system. This type of failure is known as an initial failure or early failure. Few failures occur randomly. This type of failure is categorized as catastrophic failure. After a useful life of the system, the failure rate increases due to a decrease in efficiency of the component of the system. This type of failure is known as wear-out failure [1].

A curve that shows the different modes of the failures, known as bath-tub curve, is shown in the following screenshot:

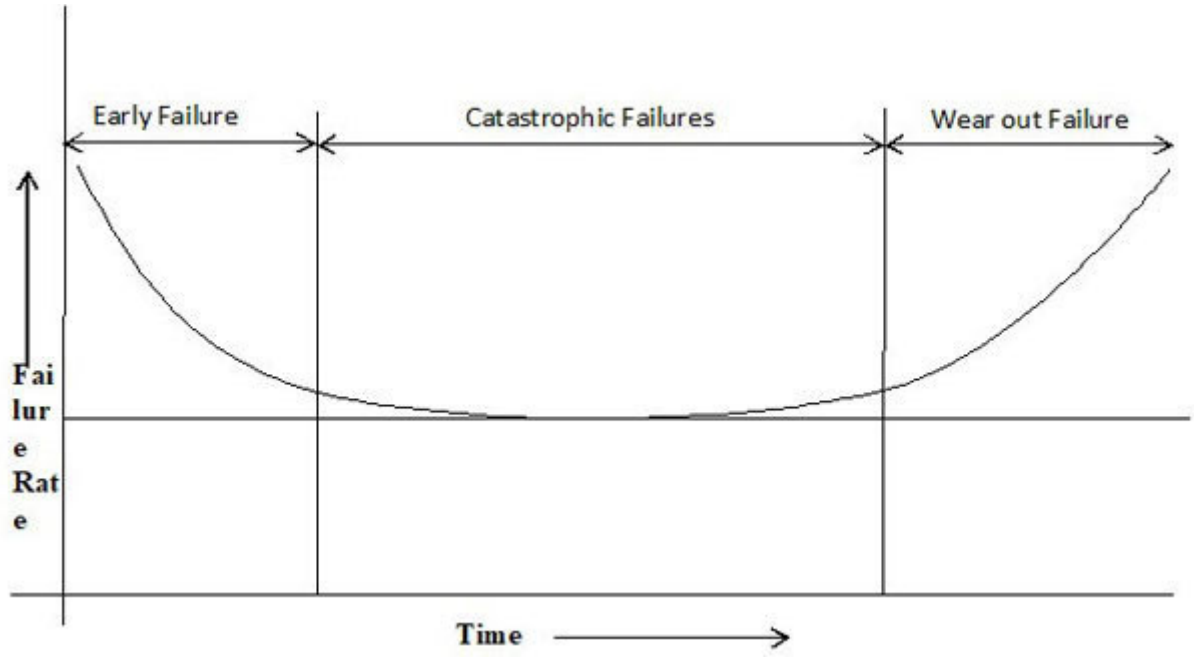


Figure 2.3: *Bath tub curve*

There are many causes that play a very important role in the failure of the system. Some of these are covered in the next sections.

Defects in the designing of the component

The main cause of failure of the system is poor designing of the component of the system. Suppose a component of a system is improper in shape, using incorrect manufacturing techniques or materials, then it will affect the failure-free operation of the system [4]. So, proper designing and improved techniques are necessary for a proper utilization of the system.

Operating conditions

The **operating conditions** represent the conditions that are helpful for the operation of the system successfully. The operating conditions are not same for every component. The complete knowledge of operating conditions reduces the frequent occurrence of the failures.

Major Failure

A **major failure** is a failure in which the system completely fails. The maintenance time and cost is very high in a major failure. It can happen at any time of the operation of the system. The functioning of the system is a very time taking process.

Minor Failure

A **minor failure** is a failure by which the system fails partially. In this type of failure, the system can easily restore in functioning condition. Time and cost of the maintenance are very low. It can also happen at any time of the operation of the system.

Common Cause Failure

Common cause failure is a failure that occurs by a common fault in the operation of the system. Common cause failure is a failure of multiple components with respect to any common cause. The poor designing, improper maintenance, manufacturing defects in the components of the system etc., are the main factors of common cause failure.

Catastrophic Failure

Catastrophic failure is a failure that occurs due to a natural disaster, such as flood, earth quake etc. In this type of failure, the system fails for a long period of time. It is very difficult to predict the time of occurrence of a failure, so it is also known as a random failure.

Human Error

Day by day automatic techniques are involved in the operation of the system/machine, but it is not possible to eliminate the human involvement in the operation of them. **A human error** means an error that's made by a human. In many situations, a human error may be present due to lack of knowledge in the operation of the equipment, unskilled worker, careless in working, improper mechanism and so on. It is not possible to eliminate all human errors, but we can reduce them by proper selection and training of the person [15, 16].

Failure Frequencies

In reliability analysis, there are mainly three types of failure frequencies.

Failure density

If a component of the system operates at time zero, then the failure density is the probability per unit of time that the component gets its first failure at time t.

Failure rate

If a component operates at time zero and survives to time t, then the failure rate is the probability per unit time that a component gets failure at time t.

Conditional Failure Intensity

If a component was operating or after repairing it was operating from time zero to t, then the conditional failure intensity is defined as the probability per unit time that the component gets failure at time t.

Maintenance

The operating period is the most important period in the life cycle of the system. Every system is likely to fail since no system is perfect. But the life time of the system can be increased by the maintenance of the system. Maintenance Prevention is used for increasing the life cycle of the system. The main aim of maintenance prevention is to reduce maintenance cost and time.

The main objectives of maintenance prevention are as follows:

For stable operation, it reduces the time of maintenance.

It helps in the working of the system efficiently with minimum labor and balanced workload.

It minimizes the maintenance cost and loss of new equipment.

It improves the reliability of the system.

Methodology used

For reliability analysis and prediction, various models are used, such as Markov chain and Markov process, Weibull distribution and so on.

Markov model

Markov model is a powerful tool for reliability analysis. This model was developed by Andrei Andreyvich Markov. Markov chain and Markov process are the two basic Markov analysis methods. Markov chain is used in discrete state and discrete time variable, while the Markov process is used in discrete state and continuous time models.

The Markov model has the following assumptions:

If λ is the failure rate, then $\lambda \Delta t$ represents the transitional probability from one state to another state in time interval Δt.

If time interval , then the probability of more than one transition from one state to another state is negligible.

All occurrences are independent ofeach other.

Let the system have only two states and f(t) be the hazard rate of the system [1].

State 0: The particular part is operable.

State 1: The particular part fails.

The Markov graph is shown in the following screenshot:

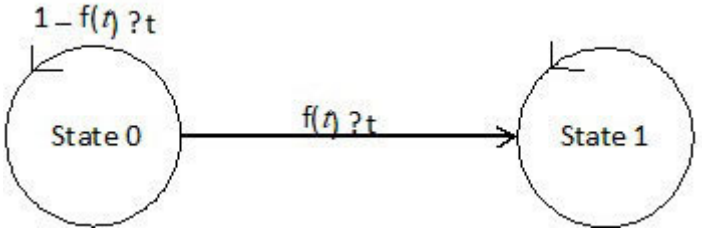


Figure 2.4: *Markov Graph for two states*

The probability that the particular part will fail in time interval Δt is f(t) Δt, where the part is in state 0 in time t and reached in state 1 in time Δt.

The probability that a particular part is in state 0 at time t+Δt, is given by the following formula:

$$P_0(t + \Delta t) = P_0(t) - f(t)\Delta t P_0(t)$$

The probability that a particular part is in state 1 at time is given by the following formula:

$$P_1(t + \Delta t) = f(t)\Delta t P_0(t) + P_1(t)$$

If we assumed a constant failure rate λ and constant repair rate μ, then the outcome is shown in the following Markov graph:

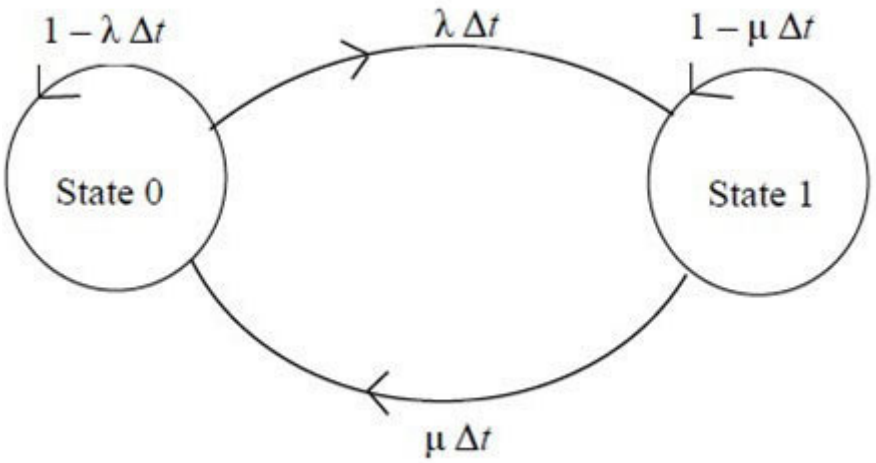


Figure 2.5: *Markov Graph with constant repair rate*

In state 0, no failure occurs and in state 1, one failure occurs. The probability that a particular part fails in the time interval t + is λ Δt, and the probability that after repairing, a particular part will enter in state 0, is μ Δt.

Therefore, the probability that a particular part will be in state 0 at time $t + \Delta t$ isas follows:

$$P_0(t + \Delta t) = P_0(t)(1 - \lambda\,\Delta t) + P_1(t)\mu\Delta t$$

The probability that a particular part will be in state 1 at time t + Δt is as follows:

$$P_1(t + \Delta t) = P_1(t)(1 - \mu\,\Delta t) + P_0(t)\lambda\Delta t$$

Supplementary variable technique

Supplementary variable technique was first introduced by D. R. Cox in 1955. This technique is used for the modelling of a system that contains constant failure rates and non-exponentially distribution repair rate. The construction of modelling is done by Markov process and supplementary variable technique. This technique provides a systematic solution for finding reliability and availability of the system.

If the failure and repair rates are a function of time, then the system is non-Markovian. For converting the non-Markovian system into the Markovian system, we introduce some variables which are known as supplementary variables. By using these variables and using the Markov process, one can obtain the different transitional states' probability of the different states.

Laplace Transformation

Laplace transform is an integral transform. It was discovered by Pierre Simon Marquis De Laplace. Pierre Simon Marquis De Laplace was a great mathematician and a professor in Paris. Laplace transform is the most important operational method. Laplace transform method solves the differential equation and partial differential equation. Laplace transform is a very useful technique for engineers. The process of solution consists of the following three main steps:

The given problem is transformed into a simple equation.

The subsidiary equation is solved purely by algebraic manipulation.

The solution of the subsidiary equation is transformed back to obtain the solution tothe given problem.

Let f(t) be a function defined for t ≥ o. If we multiply f(t) by e-st and integrate with respect to t from zero to infinity, then we get a function of s, i.e., F(s) is defined as follows:

$$F(s) = \int_0^\infty e^{-st} f(t) dt$$

This function of the variable 's' is called the Laplace transform of

The function is called the inverse Laplace transform and is written as follows:

$$f(t) = L^{-1}\{F(s)\}$$

Need for reliability analysis

In this modern age, reliability becomes a major and critical issue. The electronic devices or gadgets are made up of various tiny components. The failure of one component can degrade the whole system or shut down the complete electronic gadget.

The need forreliability analysis is as follows:

Long term reliable operation of electronic device.

The 'reuse' potential of electronic components.

The problem of e-waste can be minimized as the same component can be reused again and again, rather than being discarded.

The warranty issues can be resolved.

The market reputation of manufacturer can be protected.

The remaining useful lifetime or residual life can be predicted.

The upcoming fault or failure can be pre-diagnosed.

So, the reliability analysis or residual lifetime assessment becomes a very challenging issue for manufacturers, consumers, and users.

Electronic components failure mode and mechanism

When designing systems containing electronic components, it is valuable to an engineer to have the knowledge of component failure modes and mechanisms and their probability of occurrence. These factors are also invaluable to an analyst when performing failure analyses and developing recommendations to eliminate the future occurrence of failures. The following *Table 2.1* presents failure modes and mechanisms for a representative group of electronic components. The data used to prepare this table was collected by the Reliability Analysis Center in Rome, New York.

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Table 2.1: *Failure Mode Distribution of electronic components*

Conclusion

This chapter signifies the importance of reliability analysis and diagnosis using various models, such as Markov and Weibull. The significant failures and modes of electronics and electrical components are discussed in this chapter.

In the next chapter, different types of reliability prediction techniques are elaborated, such as empirical method, experimental method, and analytical method.

Questions

How does reliability reduce the worldwide problem of 'electronic and electrical waste'?

How are reliability and validity inter-related?

What do you mean by electronic components failure mode? Mention at least five electronic components along with its failure mode and mechanism.

What is the significance of Markov method?

Explain the concept of 'sensitivity analysis'.

Differentiate between repairable and non-repairable systems.

What do you mean by conditional failure intensity?

How will you define the terms 'unreliability' and 'operational availability'?

How are probability and reliability needed in our daily life?

CHAPTER 3

Remaining Useful Lifetime Estimation Techniques

Introduction

As the electronics industry is growing on an accelerated pace, the electronics and electrical gadgets become obsolete after the invention of new technology. In 2014, a total of 41.8 metric kilo tonnes of waste electronics and electrical equipment was generated globally. Once the electronics and electrical product becomes outdated, their components become unaltered. These components can be reused, if their remaining useful lifetime can be predicted. The lifetime claimed by datasheet may vary according to real time applications.

Structure

In this chapter, we will discuss the following:

Remaining Useful Lifetime analysis

Regression analysis

Experimental techniques

Empirical techniques

Mathematical modelling

Objectives

After studying this chapter, you should be able to explore various statistical and test methods and techniques for remaining useful lifetime analysis, such as regression analysis, experimental techniques, as well as empirical techniques, such as military handbook MILHDBK217F. In the Arrhenius and acceleration factors based mathematical modelling, the condition and health of components are monitored Further, the Importance of analytical and empirical methods of failure prediction is analysed.

Importance of failure prediction

A failure of a single component can damage the whole equipment. So, failure prediction of electronic components is a critical issue to be targeted for successful operation of the device, as well as to minimise the electronic waste. Such an assessment is attempted to in this research work. The methodology involves selection of a suitable component for assessment, followed by the prediction of its failure. A review of the basics of reuse philosophy is made along with the merits of component reuse and is highlighted in this chapter. The development of the prediction model for the failure assessment is discussed and In this chapter, the development of a prediction model for each of the techniques is detailed. *The later part* discusses the regression model for prediction. The empirical method for RUL prediction is elaborated in the last section of this chapter.

Reuse

The definition of **reuse** of components is given by Fatida et al. (2009), *"An action or operation by which components are used for the same purpose for which they were conceived without any prior treatment apart from disassembly, cleaning, testing, and reassembly."*

Component reuse

The option of **component reuse** exploits the fact that components, in general, have a much longer life cycle than the corresponding product. Some of the components may still be well-functioning even if the performance of the product as a whole is unacceptable. The following screenshot shows the well-known bathtub curve for a product and its components:

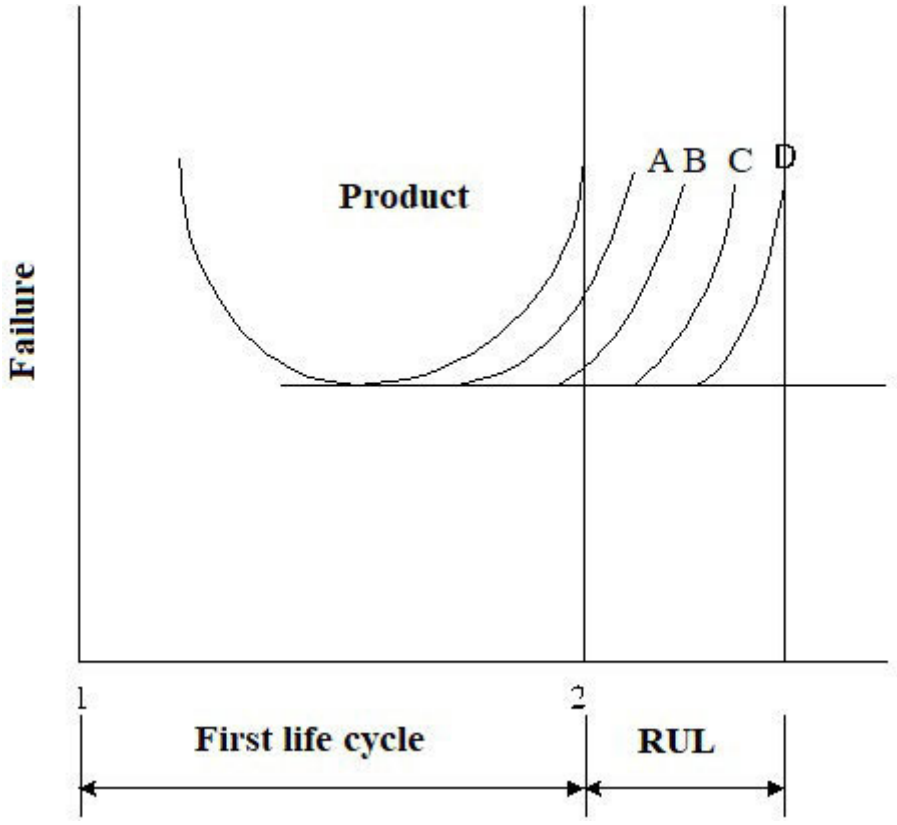


Figure 3.1: *Bathtub curves for a product and its components*

The preceding screenshot implies that although a parent product as a whole fails, some of its components may be reusable due to their longer useful life (Parts A to D in *Figure* The traditional approach of discarding the whole product along with its components at its first life cycle (1 to 2 in *Figure* results in wastage of resources that could have been reused, now that the components A to D in *Figure 3.1* are yet to complete their life cycle. Discarding them at this point of time amounts to wasting of resources that could otherwise have been used for a further period of time. The objective of the research is to develop a set of models to assess the RUL of used components, as also to highlight the potential of the reuse philosophy.

Merits of component reuse

Exploring the reuse potential of electronic and electrical components has the following merits:

Conservation of energy and resources

Material going to land fill gets reduced

Ensures a green environment

Failure prediction of electronic components

The concept of **failure prediction** life has originated from the fact that a certain number of components/parts of a product have an operating life that exceeds the life of the product itself. The unused potential of these components can be better utilised if there is a reliable method to accurately assess this potential or under real time applications, there is variation in environmental stress and electrical parameters, which can make a component vulnerable. Excessive range of operating parameters may reduce the life of a component. Sudden failure of a component may lead to catastrophic failure and shut down the complete system.

Various definitions of failure prediction of a product are proposed in literature. In this thesis, failure prediction is defined as a function of the component's overall life (total life) and the actual (used/consumed) life under the operating conditions of use. The failure prediction can also be estimated by subtracting the consumed life from the total useful life. It is similar to estimating residual life.

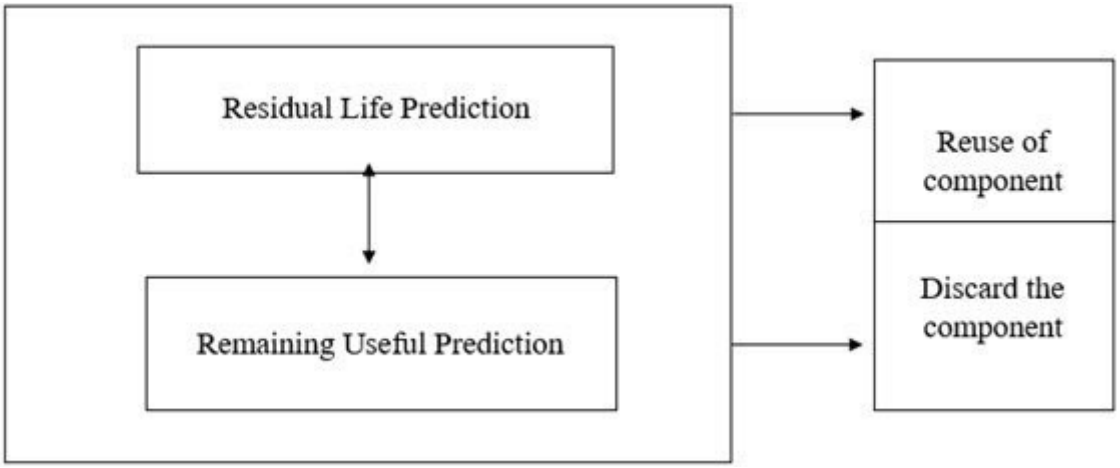


Figure 3.2: *Key factors of Failure Prediction*

Techniques for RUL prediction

For predicting RUL, three major techniques are used:

Statistical technique

Experimental technique

Empirical technique

Intelligent model

For **statistical** multivariable regression is used, which can be implemented using Minitab 18.1. The **experimental technique** uses accelerated life testing, for estimating the residual lifetime. The **empirical methods** are the standard methods, which are used for condition monitoring of the electronic components. The **intelligent model** used artificial intelligence techniques such as Artificial Neural Networks, Fuzzy logic, and **Adaptive Neuro Fuzzy Inference System** models, which are used for predicting the remaining useful lifetime of the component.

The proposed methodology predicts the failure and useful remaining life in two stages. Selection of components with reuse potential forms the first stage. The second stage deals with the prediction of the total residual life of these components using

different techniques, which predicts the upcoming failure of that specific component. *Figure 3.3* shows a procedural frame work employing the previously mentioned methods for the development of a failure prediction model.

Selection of component for failure assessment

Electronic components are the backbone of an electronic industry. In general, these components are found to have some useful life left even after their regular usage. When the manufacturer launches a component or equipment in real world, it often comes with a datasheet, which claims the operating range of parameters, as well as rated lifetime. But actual application or environmental condition may reduce or exceed its actual life. **Predicting failure** is a step to identifying the reuse potential, and it acts as a safety parameter for successful operation of gadget. An **electrolytic capacitor** is an application-oriented passive component, which is used in most of the electronic applications. Similar is the humidity sensor, which has usage from daily life to military applications. As such, the accurate assessment of failure of these components is of great significance in any electronics industry. This exercise will in turn reduce the overall repairing cost and help achieve enhanced productivity. This aspect of the failure prediction and re-use of the components has not been discussed sufficiently by researchers.

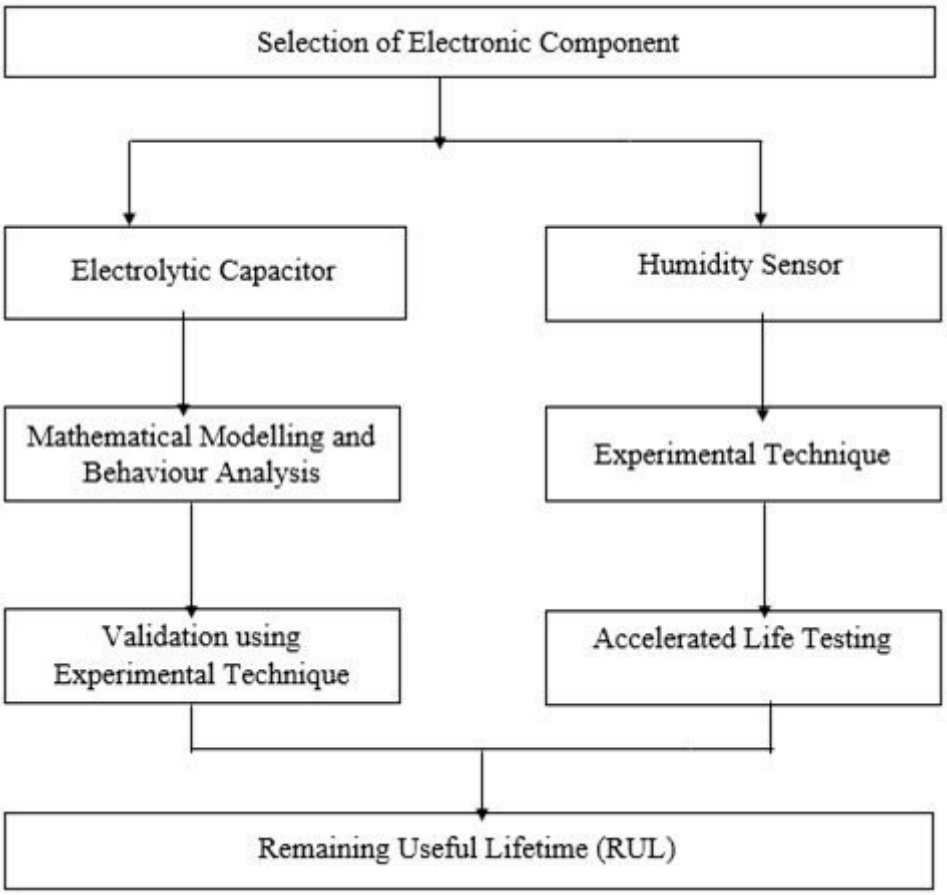


Figure 3.3: *Analysis of Actual Lifetime (hours)*

Collection of failure data

After selecting the electronic components, the next step is to explore their behaviour analysis. The critical parameters are decided based on literature. Based on these critical parameters, the behaviour of the components has been analysed. Using mathematical modelling, an analytical method has been suggested. It has been validated using practical approach. For experimental collection of failure data, accelerated life testing methodology is used. The failure of the components is analysed and collected using Arrhenius equation. A digital hot plate is used for varying temperature on an accelerated pace. After collecting failure data using experimental approach, as well as using proposed analytical approach, a comparison has been made. On the basis of error analysis and accuracy estimation, the proposed method is validated. Actual lifetime is gathered for further processing.



Figure 3.4: *Digital hot plate for accelerated life testing*

Failure prediction using artificial intelligence techniques

The failure time of the components are accessed using proposed analytical method, as well as experimental approach. Actual lifetime or failure time is analysed based on comparison between these two techniques. Using Minitab 18.1 software, statistical analysis of the failure data is conducted. An expert system has been modelled using various artificial intelligence techniques, i.e., artificial neural networks, fuzzy logic, and adaptive neuro fuzzy techniques.

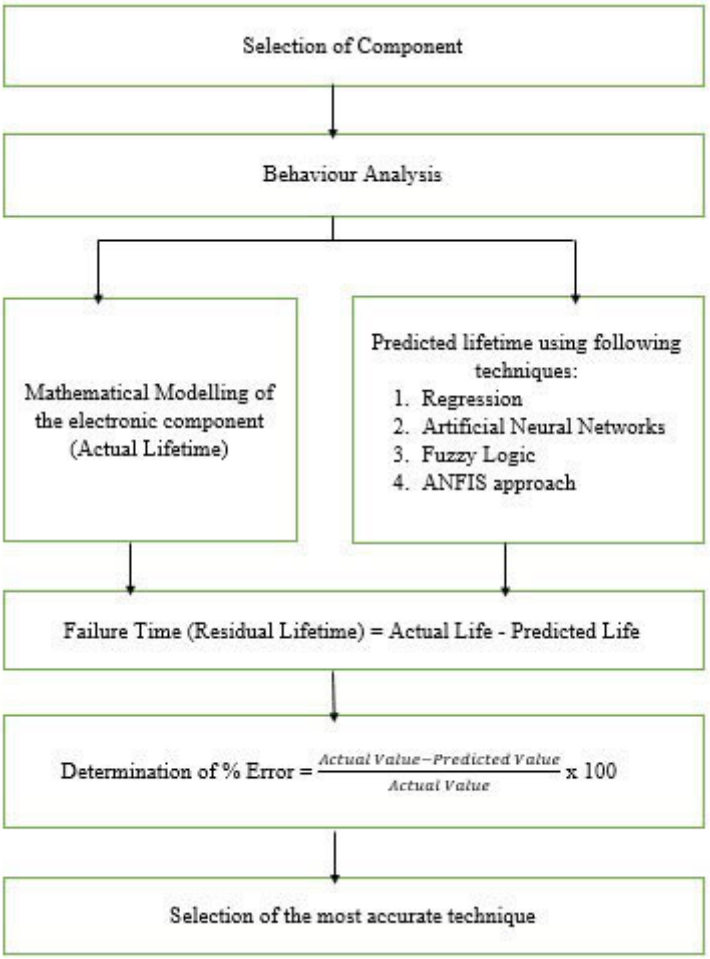


Figure 3.5: *Methodology for Failure Time (Residual Lifetime) Assessment*

Data driven techniques namely regression, artificial neural networks, fuzzy logics, and adaptive neuro fuzzy techniques are selected for analysing and investigating the data to predict the residual life of components under the given conditions of use.

Comparison of techniques

The response calculated using various prediction techniques and statistical techniques is compared with the actual life. The error analysis has been conducted. Based on the highest accuracy, the model has been identified for prediction of failure. A fuzzy based graphical user interface is framed, which accesses the health condition of the component based on the output response. *Figure 3.5* illustrates the estimation methods which can be used in predicting the failure of components.

Mathematical model

Mathematical model is an abstract model that uses mathematical language to describe the behaviour of system. Mathematical model may be represented using analytical, statistical, or numerical form of variables and response. Failure predicted of an electrolytic capacitor is explored using the mathematical model.

Electrolytic capacitor

An **electrolytic capacitor** is a type of passive component which uses an electrolyte to achieve larger capacitance than other types of capacitors. It is extensively used in manufacturing and design industries. The electrolytic capacitor is widely used due to its low cost and small size.

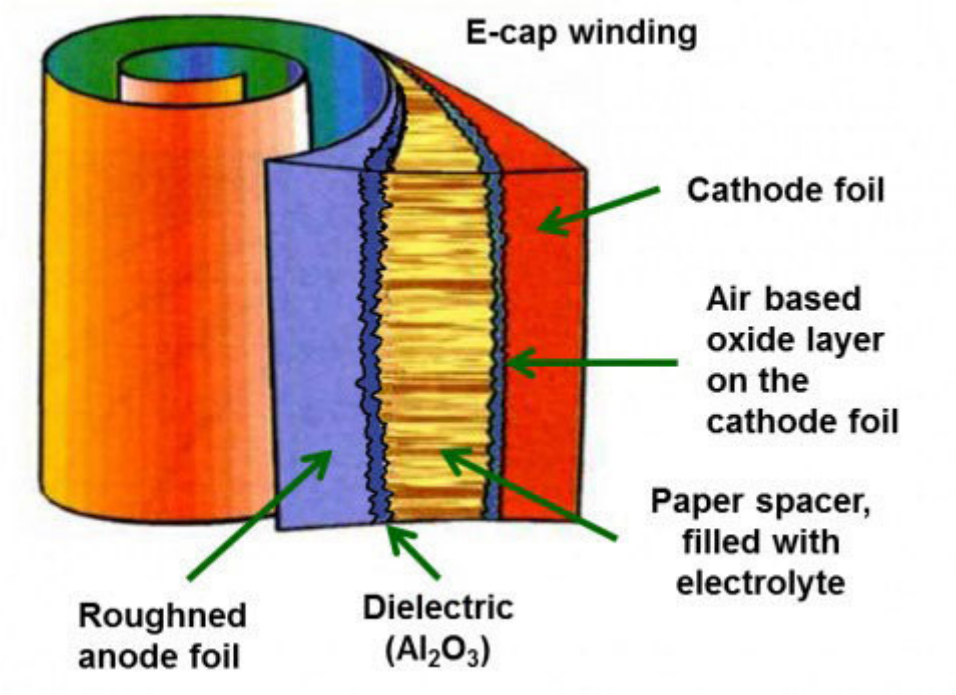


Figure 3.6: *An aluminum electrolytic capacitor (Image credit:*

To analyse the failure and behaviour of electrolytic capacitor, a fishbone diagram is represented in the following screenshot. It explores the cause of failure and effect on the behaviour of electrolytic capacitor.

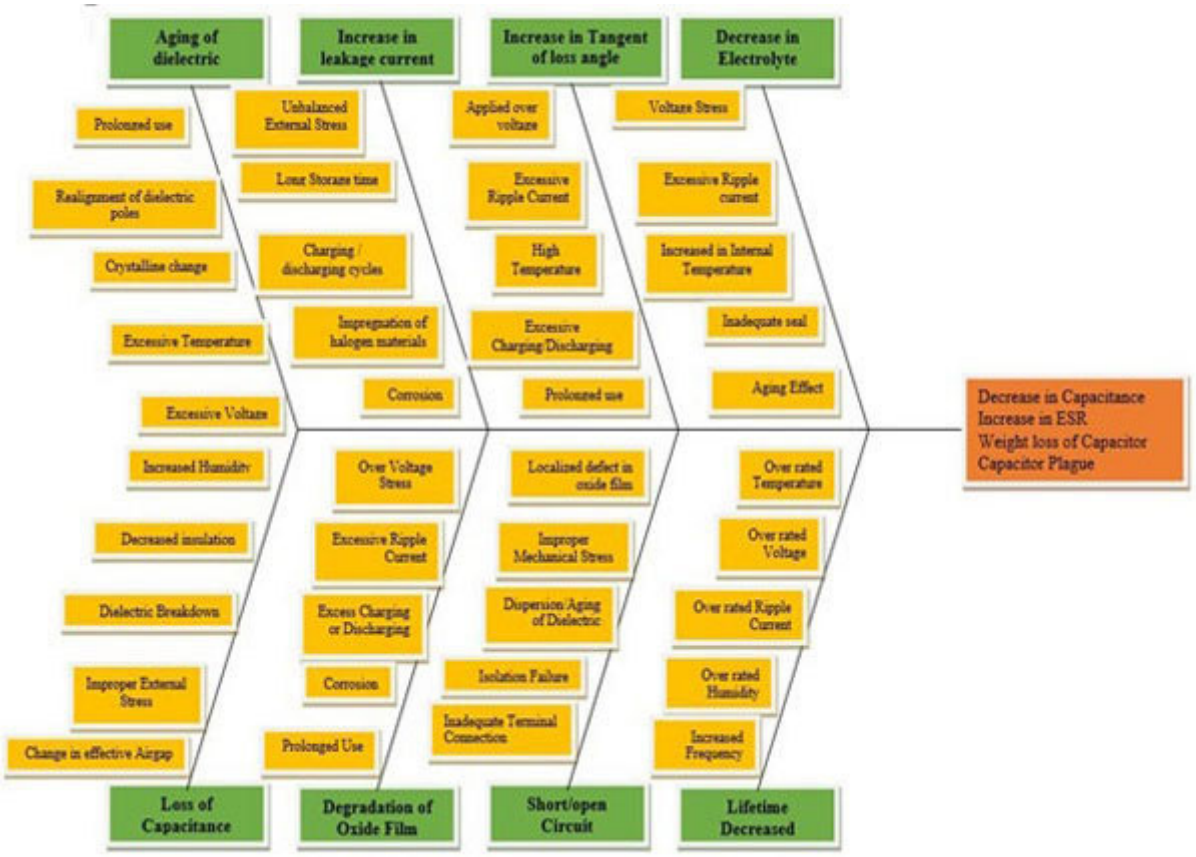


Figure 3.7: *Fishbone diagram of an electrolytic capacitor*

Furthermore, this cause and effect diagram explains the different parameters that can degrade the performance, as well as life of an electrolytic capacitor[2]. The failure of an electrolytic capacitor is detected, if there is significant change in capacitance, weight or ESR value. Literature shows that temperature, voltage, ripple current, and ESR parameters change the lifetime of the capacitor. The thorough study of variable input and output parameters is conducted to carry out health prognostics and condition monitoring of capacitor. After exploring, it is concluded that humidity is also an important variable which affects the performance of capacitor, along with other factors, such as temperature, voltage, ripple current and ESR.

Behaviour analysis of electrolytic capacitor

During design and manufacturing phase of an electronic component, its lifetime is explored at different operating conditions and a datasheet is prepared, which claims maximum rating parameters, as well as the lifetime of that specific component. But after releasing the component to the market, it may be put on off-shelf or installed on a critical environmental condition such as military or satellite applications. In such type of applications, the input parameters may vary on an accelerated pace. Due to severe operating conditions, the performance may deteriorate and simultaneously the lifetime may change as compared to the lifetime as claimed by datasheet.

So, while designing mathematical model of electrolytic capacitor, input parameters are taken as temperature, voltage, current, ESR, as well as humidity and output parameters are residual lifetime, which indicates the failure time. The relation between input and output parameters are explored using mathematical relation.

Effect of temperature on lifetime of capacitor

Changes in temperature around the capacitor affect the value of the capacitance because of changes in the dielectric properties. If the air or surrounding temperature becomes too hot or too cold, the capacitance value of the capacitor may change so much as to affect the correct operation of the circuit. Generally, for electrolytic capacitors and especially aluminum electrolytic capacitor, at high temperatures, the electrolyte may be lost due to evaporation, and the body of the capacitors may become deformed due to the internal pressure and leak outright. Also, electrolytic capacitors cannot be used at low temperatures, below about -10°C, as the electrolyte jelly freezes [3]. Due to the property of electrolyte used, the capacitance can significantly decrease and ESR can increase, with rise in temperature. The reason is increase in viscosity and resistance of electrolyte induced from reduced ionic mobility. Operating conditions directly affect the life of an aluminium electrolytic capacitor. The ambient temperature has the largest effect on life. The relationship between life and temperature follows a chemical reaction formula called Arrhenius' Law of Chemical Activity. Simply put, the law says that life of a capacitor doubles for every 10 degree Celsius decrease in temperature (within limits) [4]. During operation, the electrolytic capacitors' temperature rises above ambient temperature. In the steady state, the applied electrical power matches the heat power dissipated to the ambient [5]. The main cooling mechanisms for electrolytic capacitors are radiation and convection. Heat conduction is usually

very small. The capability to radiate heat depends on the electrolytic capacitors surface material. The contribution of convection to the total cooling effect can be improved by forced cooling [6].

Effect of voltage on lifetime of electrolytic capacitor

When the voltage is increased, it will accelerate the chemical reactions. The dielectric starts to form and leakage current starts increasing. As the leakage current enhances, it will automatically increase the temperature, which further cause the electrolytic capacitor to fail.

Effect of ripple current on lifetime of electrolytic capacitor

Due to larger value of tan δ in electrolytic capacitor as compared to other capacitors, the internal heat produced by capacitor is much more than other capacitors. The heat will significantly increase the temperature, and life may be affected. So, by considering the ripple current acceleration factor, the deviation in lifetime of an electrolytic capacitor is estimated.

Compared with other types of capacitors, aluminum electrolytic capacitors have higher tan δ, and therefore are subject to greater internal heat generation when ripple currents exist. To assure the capacitor's life, the maximum permissible ripple current of the product is specified.

When ripple current flows through the capacitor, heat is generated by the power dissipated in the capacitor, accompanied by a temperature increase. Internal heating produced by ripple currents can be represented by the following formula:

$$W = (Ir)^2 \times R_{ESR} + V \times I_L$$

Here, W is internal power loss; Ir is ripple current; is internal resistance (Equivalent Series Resistance); V is applied voltage, and is leakage current.

Leakage currents at the maximum allowable operating temperature may be 5 to 10 times higher than the values measured at 20°C, but as compared to Ir, is very small and negligible.

Effect of ESR on lifetime of electrolytic capacitor

All the capacitors, which have ESR, that is, internal resistance in series with capacitance, depend on the construction and dielectric material of capacitor, which is further more connected with reliability and residual lifetime of the capacitor. The ESR value is further associated with reduced efficiency and power loss. As the temperature increases, the ESR value also increases. So, ESR and temperature is directly proportional to each other. When the electrolyte decreases or connection is not proper, the value of ESR increases.

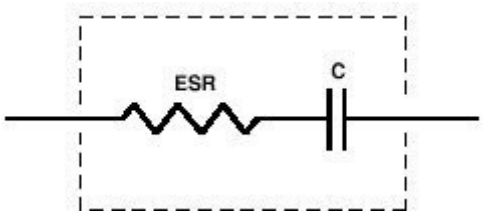


Figure 3.8: *ESR representation of capacitor*

$$ESR = \frac{DFr}{2\pi fC} + \frac{DFl}{2\pi fC} + \frac{DFd}{2\pi fC}$$

Here, is dissipation factor, is leakage losses, and is dielectric losses.

$$ESR = Rc + \frac{1}{Rl(2\pi fC)^2} + \frac{DFd}{2\pi fC}$$

Here, with increase in the value of frequency, the ESR value also increases simultaneously.

Effect of humidity on lifetime of electrolytic capacitor

The humidity is a critical factor for deciding the residual life or remaining useful life of the capacitor or any other electronic component. An increase in the humidity causes the electrolytic corrosion, which in turn reduces the value of capacitance. As per Peck's law, if the capacitor works on degraded or enhanced value of humidity, the life of capacitor reduces exponentially.

Mathematical modelling of electrolytic capacitor

Mathematical or analytical model of an electrolytic capacitor is a representation of the capacitor's behaviour in terms of numerical or statistical equations[14]. These models analyses the acceleration factor, a constant multiplier for different stress levels. Then the effect of this stress level acceleration factor is studied on the life, as claimed by datasheet. Considering all the electrical and environmental influencing parameters, the expected life has been calculated using mathematical modelling.

Consider the case of an electrolytic capacitor, which is affected by various influencing parameters, as shown in *Figure* To explore its expected lifetime under applied conditions, its behaviour is analysed for all influencing inputs, that is, temperature, voltage, current, ESR, and humidity, and acceleration factors are considered.

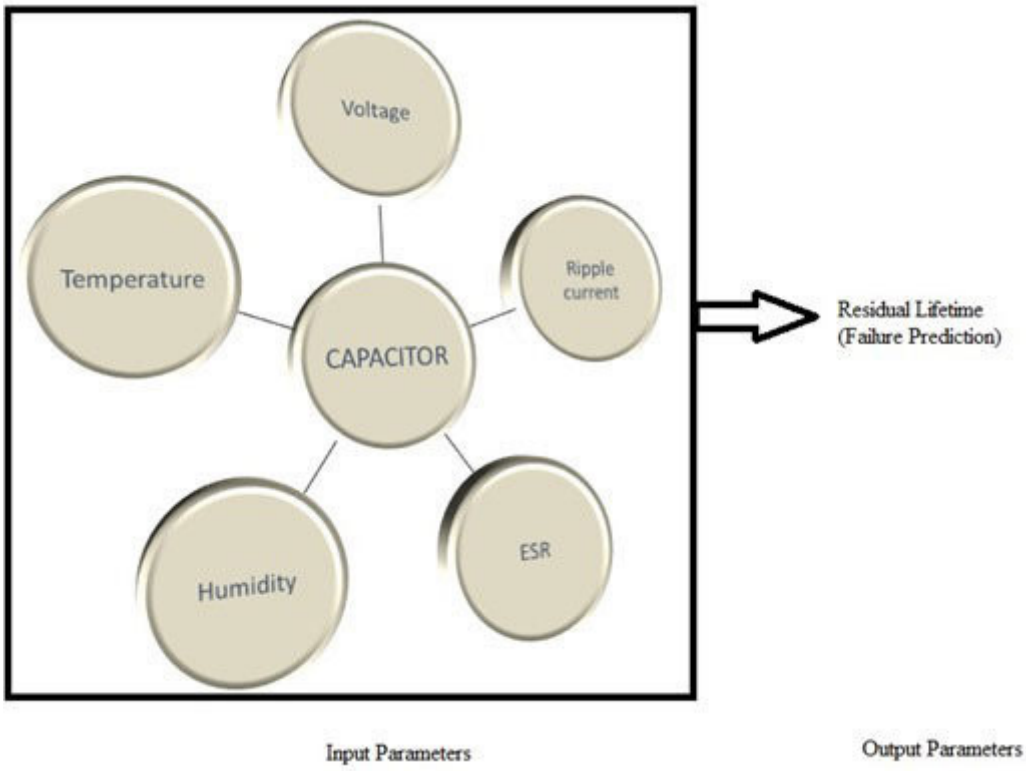


Figure 3.9: *Mathematical modelling of an electrolytic capacitor*

Let's assume the following:

Lifetime claimed by manufacturer, as per datasheet = Lifetime (D)

Lifetime expected under applied operating conditions = Lifetime (E)

Acceleration factors play an important role to access the residual life of an electrolytic capacitor. Each and every estimation parameter has its own acceleration factor, which links real time operating condition with manufacturer specified operating conditions. When a product is manufactured, it is tested under various operating conditions and lifetime, as well as maximum-

minimum range is calculated. But when the product is used in real time applications, the operating conditions may be varied, which affects the lifetime of the product. The acceleration factor explores the relation in between maximum rated condition and operating condition.

For an electrolytic capacitor, its behaviour is analysed at various environmental conditions and electrical parameters. The acceleration factors for the electrolytic capacitor for temperature, voltage, ripple current, ESR, and humidity are summarised as follows:

Temperature acceleration factor = At

$$At = 2^{\frac{(Tm-Ta)}{10}}$$

Here, Tm is maximum rated temperature (K), as specified in datasheet and Ta is applied temperature.

Voltage acceleration factor =Av

$$Av = \left(\frac{Va}{Vm}\right)^{-n}$$

Here, Va is applied voltage, Vm is maximum rated voltage as specified in datasheet, n is constant.

Ripple current acceleration factor = Ar

$$Ar = Ai^{[1-\left[\frac{Ia}{Io}\right]^2]\frac{\Delta To}{10K}}$$

Here, Ia is applied ripple current, Im is maximum rated ripple current, ΔT is increase in core temperature, Ai is empirical constant.

ESR acceleration factor = Ae

$$Ae = \frac{\sqrt{ESR(fo)}}{\sqrt{ESR(fa)}}$$

Here, ESR(fo) is value of ESR at nominal frequency and ESR(fa) is ESR value at applied frequency.

Humidity acceleration factor = Ah

$$Ah = \exp\{C \times ((RHa)^n - (RHm)^n)\}$$

Here, RHa is operating relative humidity and RHm is maximum rated relative humidity. C is constant= 0.00044

By considering the previously mentioned acceleration factors, de-rated lifetime or residual life of an electrolytic capacitor is calculated as follows:

$$Lifetime\,(E) = Lifetime(D) \times Acceleration\ factor$$

It can also be written as follows:

$$Lifetime\,(Expected) = Lifetime(D) \times At \times Av \times Ar \times Ae \times Ah$$

So, the expected lifetime or residual life can be concluded, by putting values of acceleration factors from previous equations:

$$Lifetime\,(E) = Lifetime(D) \times 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \times Ki^{A\frac{\Delta T}{10K}} \times \frac{\sqrt{ESR(fo)}}{\sqrt{ESR(fa)}} \times \exp\{C \times ((RHa)^n - (RHm)^n)\}$$

Here, expected lifetime [Lifetime (E)] and datasheet life [Lifetime(D)], both are specified in hours.

The equation represents expected lifetime (hours) for an electrolytic capacitor, when the operating conditions of electrolytic capacitor are different than the maximum rated conditions, specified in datasheet.

The actual operating life of every component depends on the real/operating conditions of use. Hence, these operating conditions must be taken into account while determining the total life and consumed life of the cutting tool. A methodology is proposed for failure estimation under different operating conditions. The total residual life of the component is determined using different techniques for a set of operating conditions.

In the proposed methodology, statistical techniques like regression, machine learning techniques like Artificial Neural Network (ANN),

Fuzzy logic, and Adaptive Neuro-Fuzzy Inference System (ANFIS) are used for predicting the residual life of the electronic components. The prediction is done based on a set of operating conditions of use.

Statistical technique

Statistical such as regression method is used to estimate the relationship of a response variable to a set of predictor variables. This capability of regression method is applied to develop a mathematical model to predict the component life. The relationship between the independent process parameter variables (temperature, ripple current, humidity, voltage, and ESR) and residual life can be represented by the following mathematical model:

$$RL \text{ (Residual life)} = C$$

Here, RL is the measure of response (residual life), t, r, h, v, and e represent the values of the process parameters, C is a model constant, and l, m, n, o, and q are model parameters.

The preceding equation can be represented in linear form as follows:

$$\ln RL = \ln C + l \ln t + m \ln r + n \ln h + o \ln v + q \ln e$$

The equation can be further modified as follows:

$$Y = +$$

Here, Y is the tool life on logarithmic scale, and are logarithmic transformations of temperature, ripple current, humidity, voltage, and ESR (i.e., = ln t ; ln r ; = ln h; ln v ; = ln e ; = ln C; =l; = m; = n; = o; = q). The values of and represent the regression coefficients to be determined. In this study, a multiple regression model using the linear regression technique is developed to predict component residual life. The coefficients for the regression model are determined using Minitab statistical software 18.1.

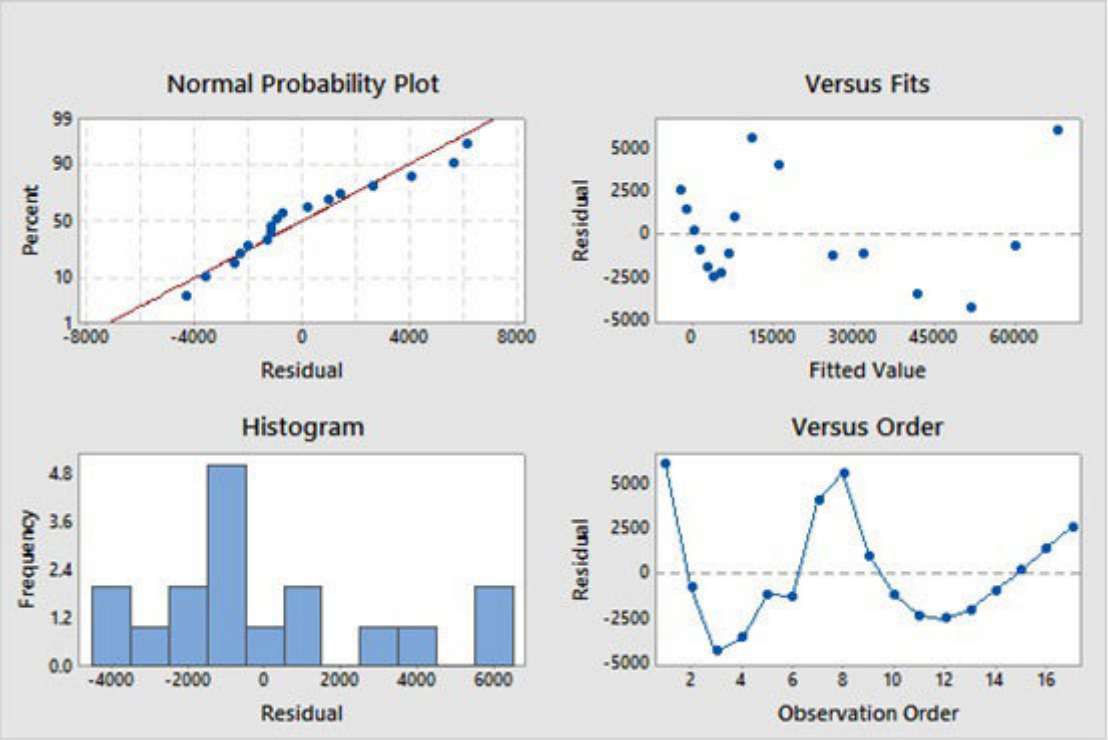


Figure 3.10: *Regression output plot using Minitab*

The regression equation has been concluded using Minitab 18.1 software. By putting different values of input, the residual life is obtained, which is compared with actual lifetime, to explore the accuracy of the regression model.

Empirical methods for RUL

Empirical standards are failure data collection resources which are accepted by recognized industries and government organization. Military handbook, Bellcore, Telecordia, RIAC, etc., are the primary sources of empirical standards. Military handbook is one of the empirical models that is based on experience and survey-based data. The MIL-HDBK-217F and MILHDBK-217-revised are two widely used versions of the military handbook. The failure data is mostly from US army maintenance data, test results, public information, or field data.

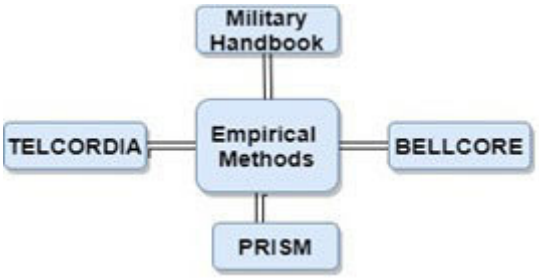


Figure 3.11: *Empirical methods for RUL prediction*

The empirical methods can be used as per the application. For example, the MILIHDBK 217F is best suited for the military applications, whereas for telecommunication applications, the use of TELECORDIA is appreciated.

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Table 3.1: *Comparison between Military Handbook and Telecorida*

Table 3.1 shows the difference between two empirical methods such as military handbook MILHDBK 217F and TELECORDIA. The problem with empirical methods is that the data available in the standard or empirical methods are not up to date. The data is not much reliable, as it is generated on the basis of general views.

Case study of electrolytic capacitor

A new mathematical model (analytical method) has been proposed for electrolytic capacitor, which predicts residual lifetime (failure time) in hours. The lifetime is calculated using mathematical model and regression analysis.

Failure prediction of electrolytic capacitor using mathematical model

Taguchi's method, as DOE approach, has been used to design experiments. Five predictor variables (factors) at five different (levels) have been taken and lifetime has been analysed. As per Taguchi's method, 25 trials at different set of variables are created and tested. The calculated lifetime of electrolytic capacitor is summarised in the following *Table*

Table 3.2: *Actual lifetime of electrolytic capacitor using analytical method*

Here, five variable factors are taken as predictors, i.e., temperature, ripple current, humidity, voltage, and ESR. Five different levels are considered, i.e., very low, low, moderate, high, and very high for each predictor. Response is failure time or residual lifetime of electrolytic capacitors, which is denoted as lifetime (hours). It has been analysed that maximum residual life of electrolytic capacitor is 14954.043 hours.

Lifetime prediction of electrolytic capacitor using regression

Using Minitab 18.1 software, Regression equation is obtained, which will predict the values as per regression response.

The regression model is given as follows:

$$Lifetime = (-34297) + 2240.5 \times Temperature + 4124 \times Current + 4516 \times Humidity + 8580 \times Voltage + 15975 \times ESR$$

By inserting the different values (as per DOE data) of predictors, i.e., Temperature, Current, Humidity, Voltage, and ESR, the value of response, i.e., lifetime of capacitor can be predicted. The following *Table 3.3* represents lifetime predicted values of electrolytic capacitor using regression technique. It reflects that the capacitor will attain maximum lifetime, 14,768.88 hours, corresponding to the predictors having values, that is, temperature is 80°C, current is 24 milliampere, humidity is 78% Rh, voltage 5.6V, and ESR value is 10.1:

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Table 3.3: *Predicted lifetime of electrolytic capacitor using regression*

So, in such a manner, the remaining useful lifetime of electrolytic capacitor is calculated using mathematical model and regression.

Conclusion

This chapter highlights the reuse potential of electronic components in order to reduce the worldwide problem of e-waste. The validity and warranty issues are well understood with the problem of reliability failure. Different methods are used to analyse the reliability of the system. The remaining useful lifetime of electrolytic capacitor is explored in this chapter using various experimental, empirical, and statistical techniques.

In the next chapter, reliability prediction using experimental techniques will be studied, along with its MTBF and FIT calculations.

Questions

Explore the empirical methods for reliability prediction, along with its application area.

Define the following terms:

Validity

Warranty period

E-waste

Reuse

What is the difference between BELLCORE, PRISM, and TELECORDIA?

What is the need for reliability analysis in electronics industry?

What is the acceleration equation for electrolytic capacitor? Discuss its each and every acceleration factor, along with effect on performance.

CHAPTER 4

Intelligent Models for Reliability Prediction

The reliability analysis and failure prediction of the electronic components are critically needed for the successful operation of gadget and device. An intelligent model is deployed, which warns the user for upcoming fault or failure, so that the user can replace the faulty product well before its expiry/actual failure.

Structure

In this chapter, we will discuss the following topics:

Artificial intelligence techniques for RUL prediction

Artificial Neural Networks (ANN)

Fuzzy Logics

Adaptive Neuro-Fuzzy Inference System (ANFIS)

Intelligent modelling

Objectives

After studying this chapter, the students will be able to understand the need for the intelligent model for condition monitoring and health prognostics. The applications of artificial Intelligence for residual life estimation are explored in detail. The various types of artificial intelligence techniques are discussed for reliability prediction, such as fuzzy logic, artificial neural networks, and adaptive neuro-fuzzy inference system.

Introduction

An **intelligent model** is the necessity of the hour. Using the intelligent model, the condition of the component can be monitored. The live health prognosis of the component or device can be done while the component is installed in the project. An artificial intelligence based model is used to predict and estimate the remaining useful lifetime of the components.

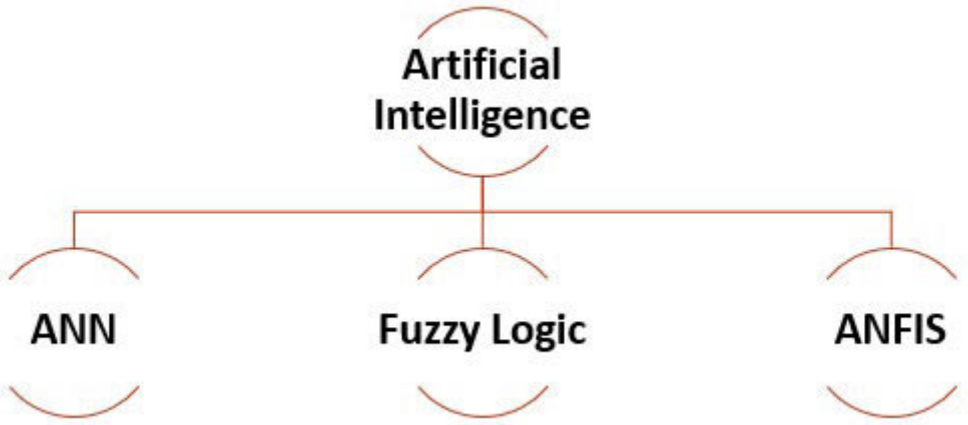


Figure 4.1: *Artificial Intelligence and its techniques*

The preceding screenshot shows the various types of artificial intelligence techniques that can be employed for the reliability analysis and RUL prediction. An early warning can warn the user to replace the faulty product or help the user to reuse the component for another project. Thus, the remaining useful life assessment helps to minimise the problem of e-waste.

Artificial neural network technique

Artificial neural network technique is one of the artificial intelligence techniques, which mimics the human brain. Using the training-testing process, the computer understands the data and validates the same, by simulation. The MATLAB 2017b NNTOOL is used for estimating the remaining useful lifetime for artificial neural network technique. Now a days, **Artificial Neural Networks** is used in industry as a data processing and condition monitoring technique. The two types of neural networks that are commonly used are supervised and unsupervised. For predicting the component life, supervised learning is used.

Structure of the neural network

In a standard structure, neurons are grouped into different layers namely input, hidden, and output layers. The structure of a feed forward three-layered back propagation neural network is shown in *figure* The 5-10-10-1 model is used for ANN. The number of neurons in the input layer consists of temperature, ripple current, humidity, voltage, and ESR, which are used to assess the residual life of electronic component, indicating the upcoming failure. There is no rigid rule for determining the number of neurons in the hidden layer.

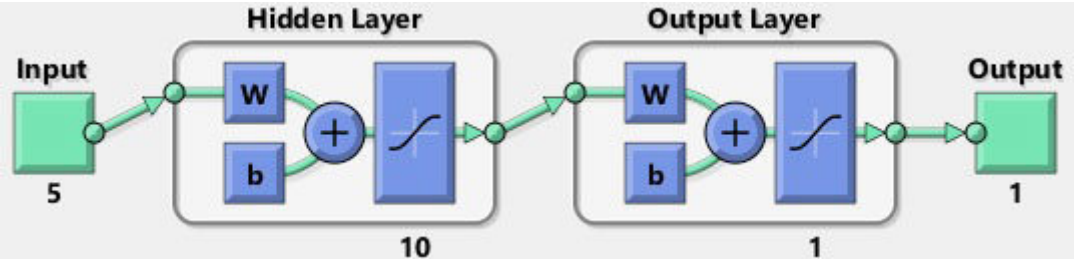


Figure 4.2: *ANN model*

The preceding screenshot represents 5-10-1-1 ANN model, in which training and testing of parameters have been done using MATLAB R2013a, and the predicted response is noted. The response obtained from ANN is compared with actual lifetime to explore its accuracy using error analysis technique.

Fuzzy logic technique

In fuzzy logic design, the fuzzification and defuzzification of data take place, which converts crisp to fuzzy and back to crisp, along with designing of rules in linguistic form. The general configuration of the fuzzy logic system is shown in *figure* There are two techniques, namely, Mamdani-type fuzzy inference system and adaptive neuro-fuzzy inference system (ANFIS). In this work, both fuzzy inference systems are selected for analysis. The fuzzy model, using Mamdani fuzzy inference, is depicted in *figure* Here, temperature, current, humidity, voltage, and ESR are used as input parameters, and life is used as an output parameter. These parameters (factors) for fuzzification use the linguistic variables, very low (VL), low (L), moderate (M), high (H), and very high (VH) as inputs. This is shown in *Table* and the linguistic variables, very low (VL), low (L), medium (M), high (H), and very high (VH) are used as the output. This is shown in *Table* A fuzzy decision rule for these inputs and output is shown in *Table* The decision rules are framed, given as follows:

Rule 1: if is and is and is and is and is then F is else,

Rule 2: if is and is and is and is and is then F is else,

. . . . . .

. . . . . .

Rule i: if is and is and is and is and is then F is else,

and are fuzzy subsets defined by the corresponding membership functions. Here, using MATLAB fuzzy tool box, three fuzzy subsets are assigned to the five inputs and five fuzzy subsets are assigned to the output. The relationship between input and output variables is developed through fuzzy rules. Twenty-five fuzzy rules are shown in *Table* Triangular, Gaussian, and trapezoidal membership functions are chosen to compare the results. Finally, the Triangular membership function is selected for input variable, which gives the least error when compared to the other membership functions.

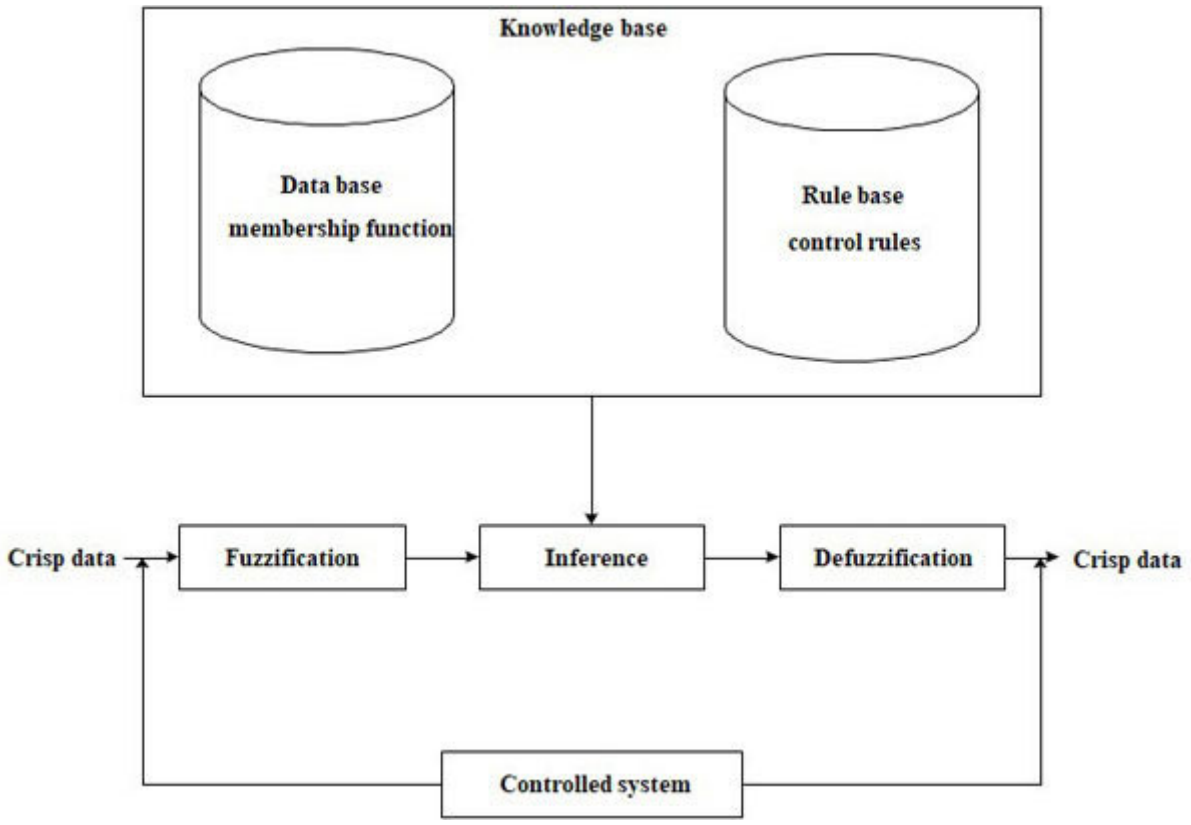


Figure 4.3: *Basic structure of the fuzzy logic system*

The various input variables, i.e., temperature, current, humidity, voltage, and ESR have been taken. Using the Mamdani model, fuzzy model is created.

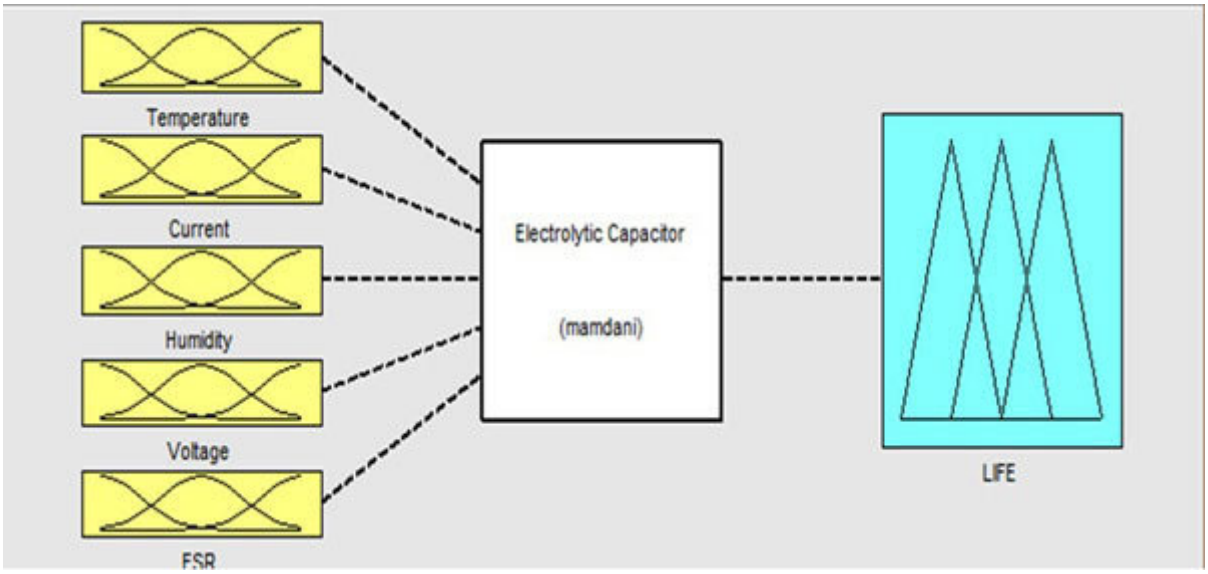


Figure 4.4: *Fuzzy model (Mamdani)*

The triangular membership function is used for input, as well as output variables. *Figures* shows input membership functions, whereas *figure 4.10* shows membership function for output, i.e., residual life.

The membership function for temperature is plotted, as shown in *figure* It has five different factors such as very low, low, moderate, high, and very high.

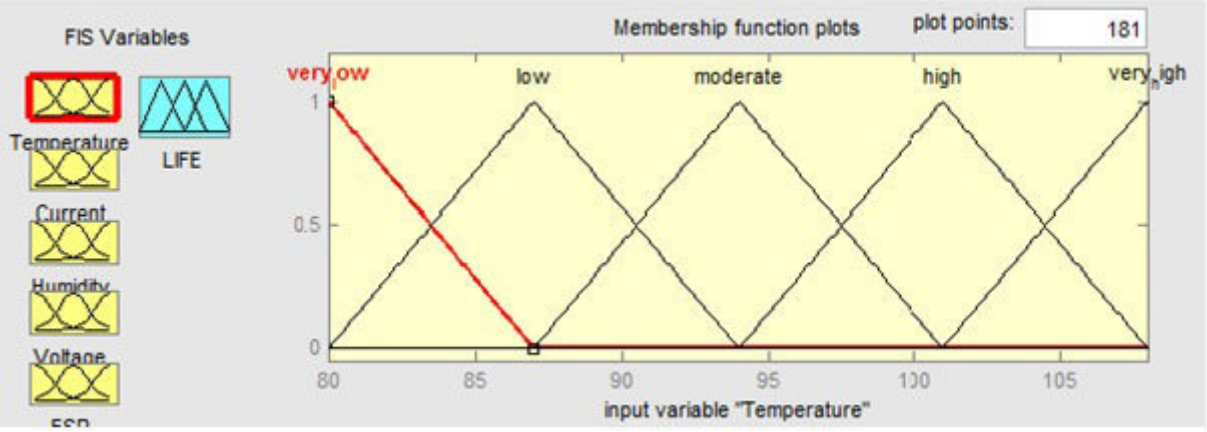


Figure 4.5: *Triangular Membership function "Temperature"*

The membership function for current is plotted, as shown in *figure* It has five different factors such as very low, low, moderate, high, and very high.

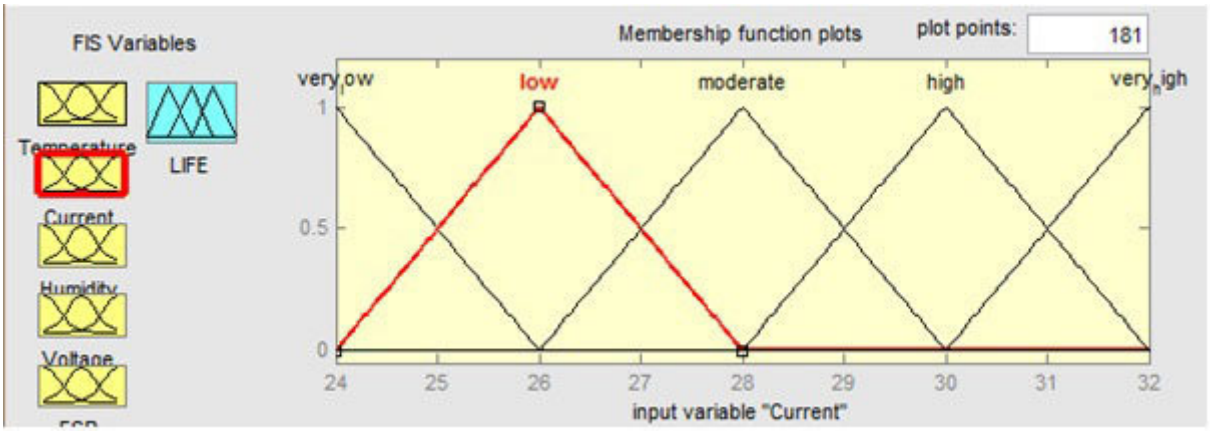


Figure 4.6: *Triangular Membership function "Current"*

The membership function for humidity is plotted, as shown in *figure* It has five different factors such as very low, low, moderate, high, and very high.

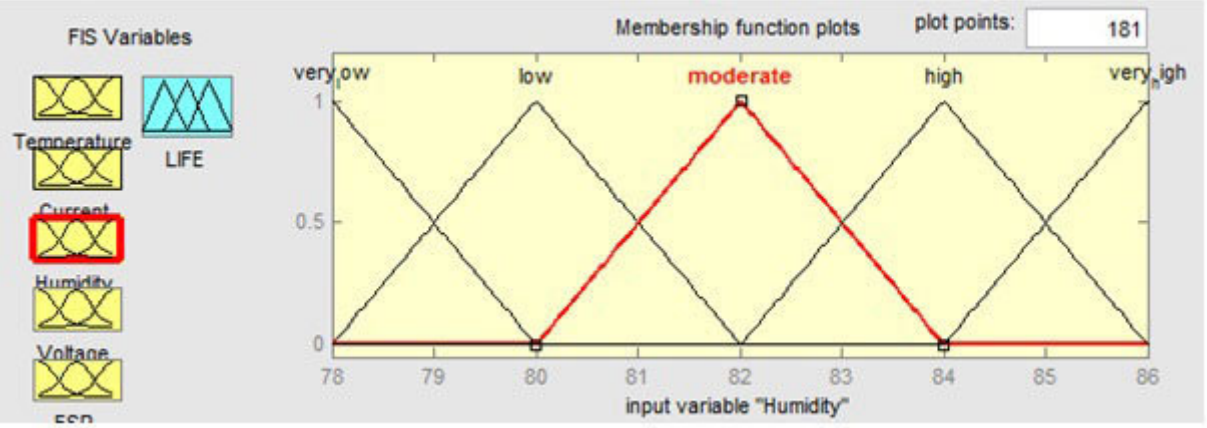


Figure 4.7: *Triangular Membership function "Humidity"*

The membership function for ESR is plotted, as shown in *figure* It has five different factors such as very low, low, moderate, high, and very high.

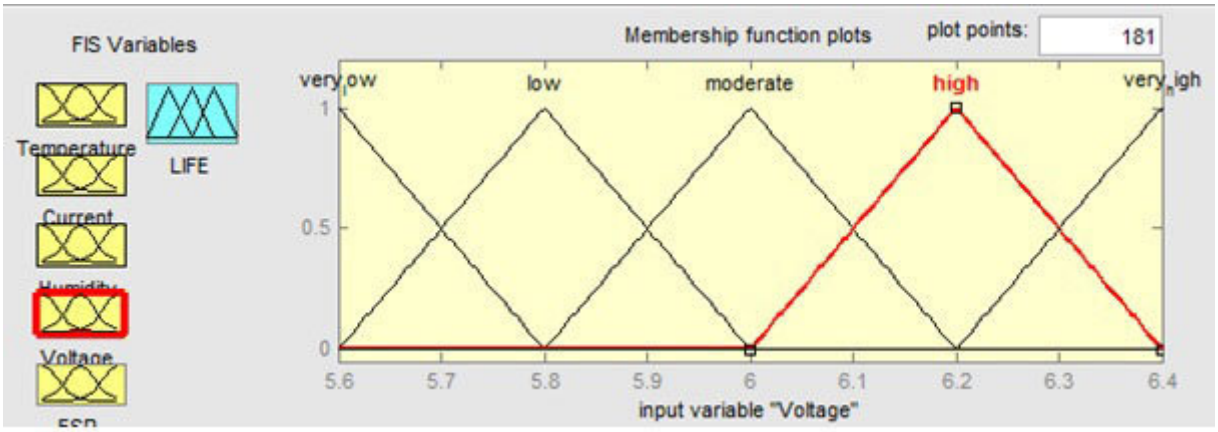


Figure 4.8: *Triangular Membership function "Voltage"*

The membership function for ESR is plotted, as shown in *figure* It has five different factors such as very low, low, moderate, high, and very high.

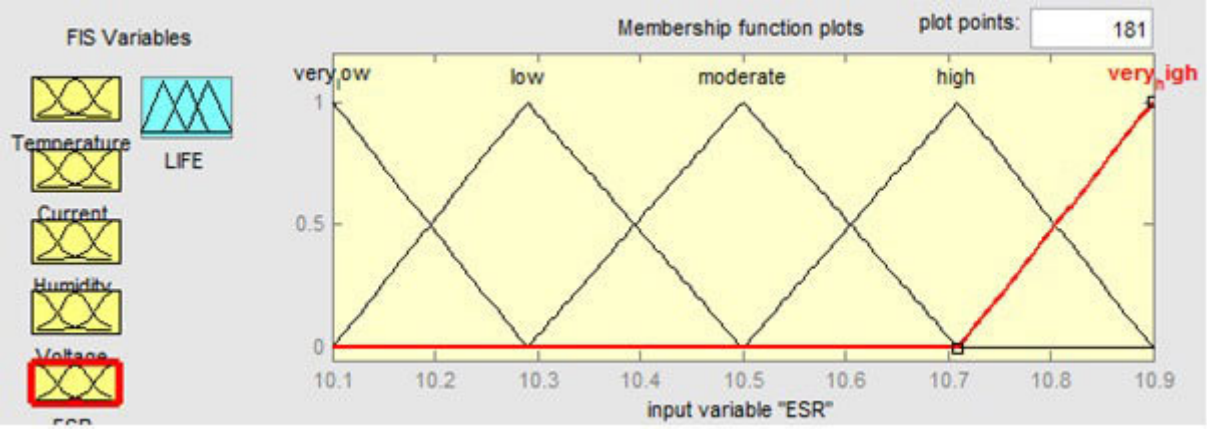


Figure 4.9: *Triangular Membership function "ESR"*

The membership function for residual life is plotted, as shown in *figure* It also has five different factors such as very low, low, moderate, high, and very high.

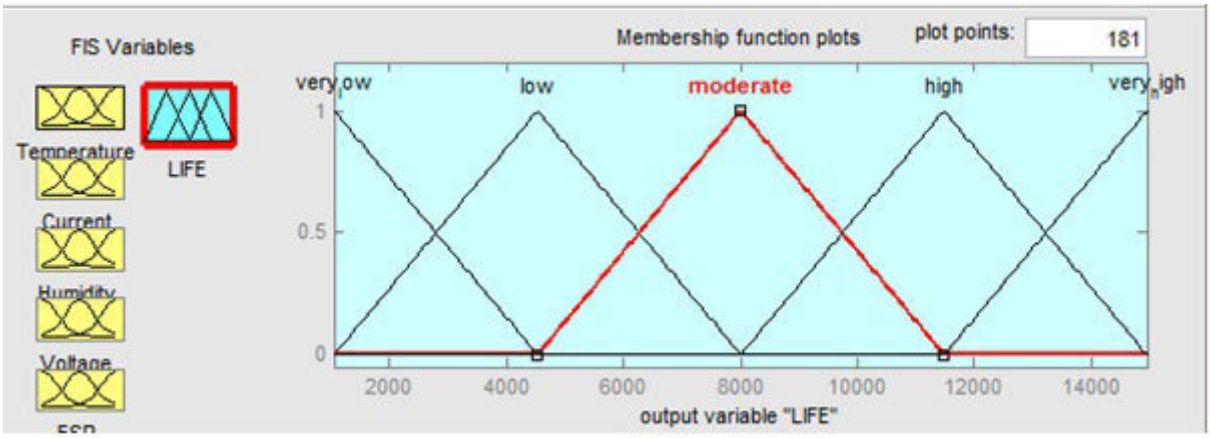


Figure 4.10: *Triangular Membership function "Life"*

The fuzzy rules are created by taking into account, all the input variables and output variable. *Table 4.1* presents the rules for various combination of inputs and outputs.

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Table 4.1: *Fuzzy rules*

The twenty-five rules are created using rule interface, which correlates the input variables with output variable. The rules are interpreted, as shown in *figure*

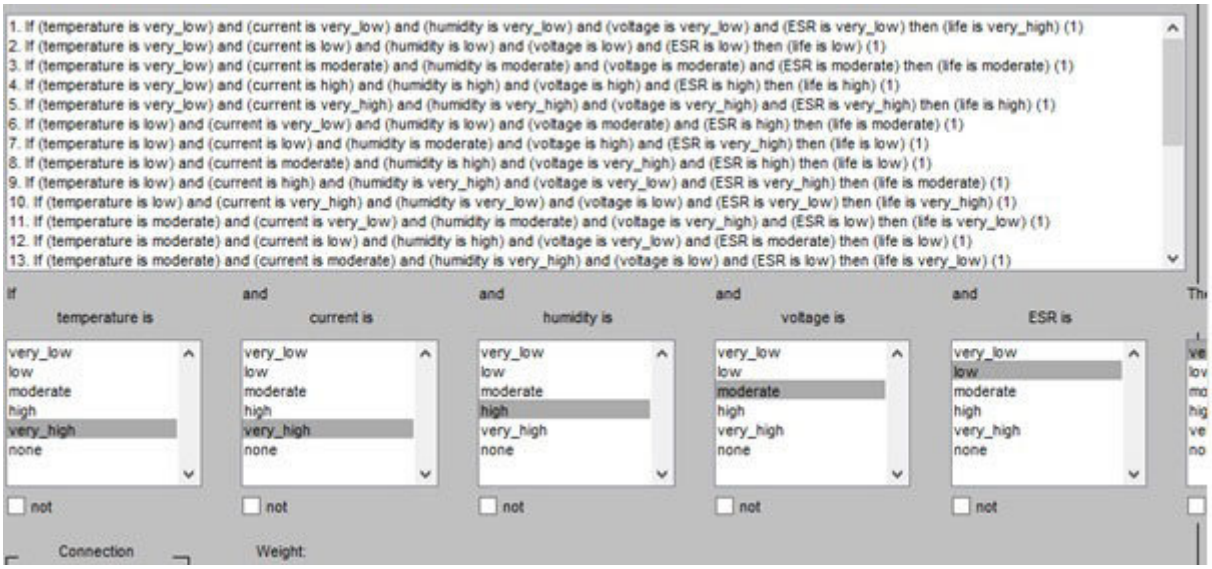


Figure 4.11: *Rules for input-output variables*

The process variables are interpreted in linguistic form, as per *table* which categorised the input and output variables as very low (VL), low (L), moderate (M), high (H), and very high (VH).

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Table 4.2: *Fuzzy input coded form*

The obtained residual life is further categorised into different levels and their linguistic interpretation, and is presented in *table*

Table 4.3: *Fuzzy output coded form*

Adaptive Neuro Fuzzy Inference System

The ANFIS is **Adaptive Neuro Fuzzy Inference** as shown in *figure* which is the combination of Artificial Neural Network (ANN) and Fuzzy Logic in Sugeno model, where the output values are optimised, and it is efficient and fast. For fuzzy based implementation, Sugeno inference system is used. It has linguistic parameters such as very low, low, medium, high, and very high, as the case of fuzzy inference system. *Tables 4.4* and 4.5 show the input and outputs.

The decision rules are framed, given as follows:

Rule 1: if is and is and is and is and is then F is (u) else,

Rule 2: if is and is and is and is and is then F is (u) else,

. . . . . .

. . . . . .

Rule i: if is and is and is and is and is then F is (u) else

and are fuzzy subsets defined by the corresponding membership functions and Pi(u) is a crisp function. Here, while using MATLAB fuzzy tool box, five fuzzy subsets are assigned to the five inputs.

The relationship between input and output variables is developed through fuzzy rules.

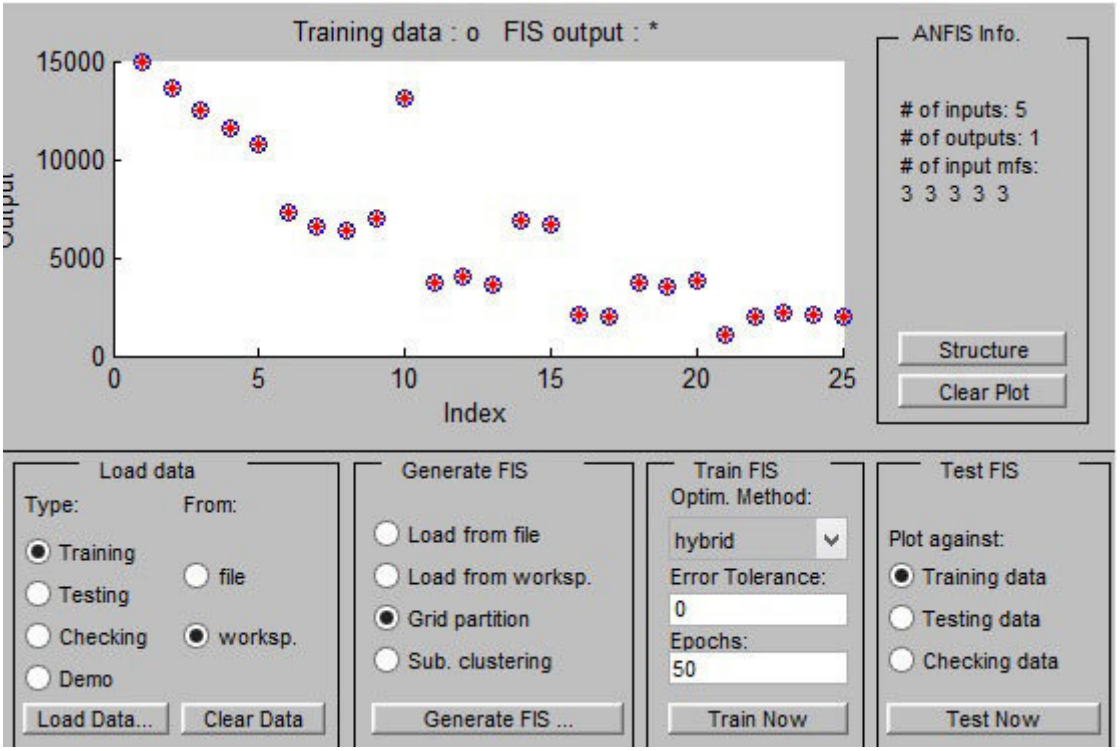


Figure 4.12: *Training and testing of ANFIS data*

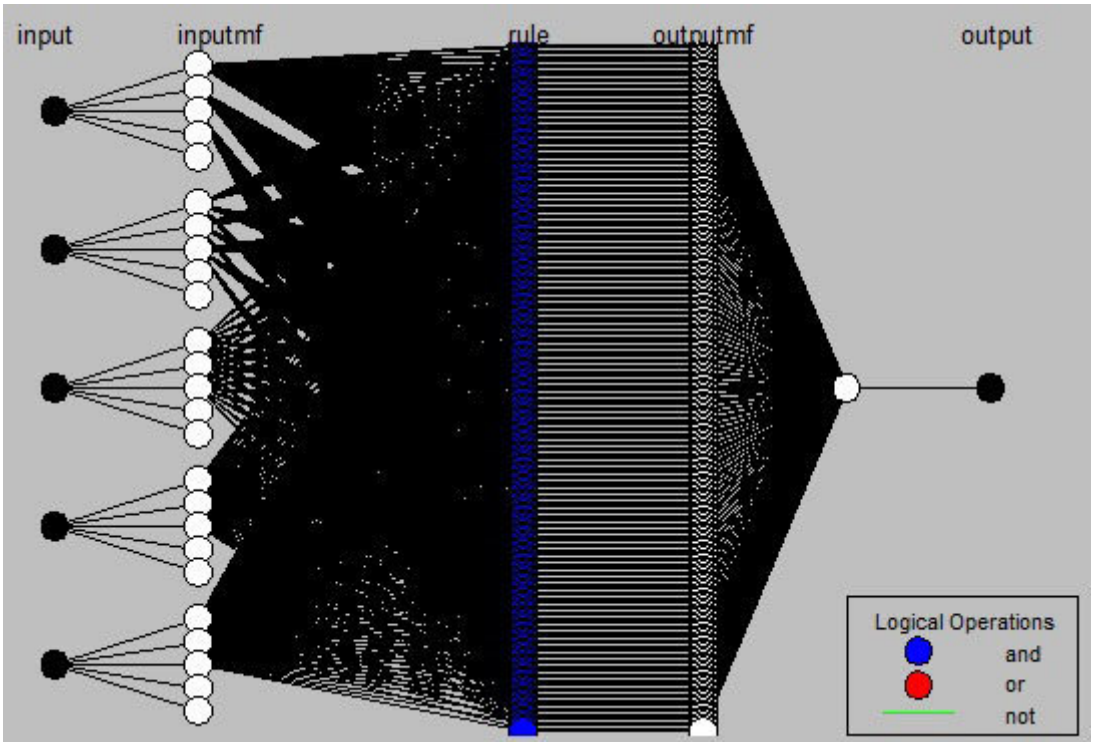


Figure 4.13: *ANFIS Architecture*

The preceding screenshot shows the adaptive neuro-fuzzy inference system (ANFIS) structure for five inputs, i.e., temperature, current, humidity, voltage, and ESR, having five membership functions each. The output is achieved as residual life of electrolytic capacitor.

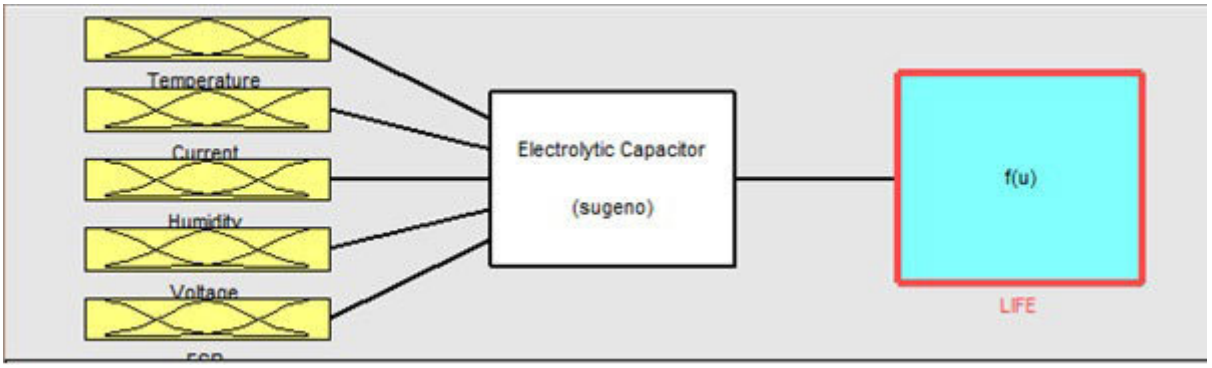


Figure 4.14: *Fuzzy model (Sugeno type)*

The Sugeno type fuzzy model is used, where output functions are either linear or constant. The gaussian type membership function is used for input, as well as output variables. The membership functions for input variables are represented in *figures* The membership functions are further categorised as very low (VL), low (L), moderate (M), high (H), and very high (VH), depending on the range of input variables.

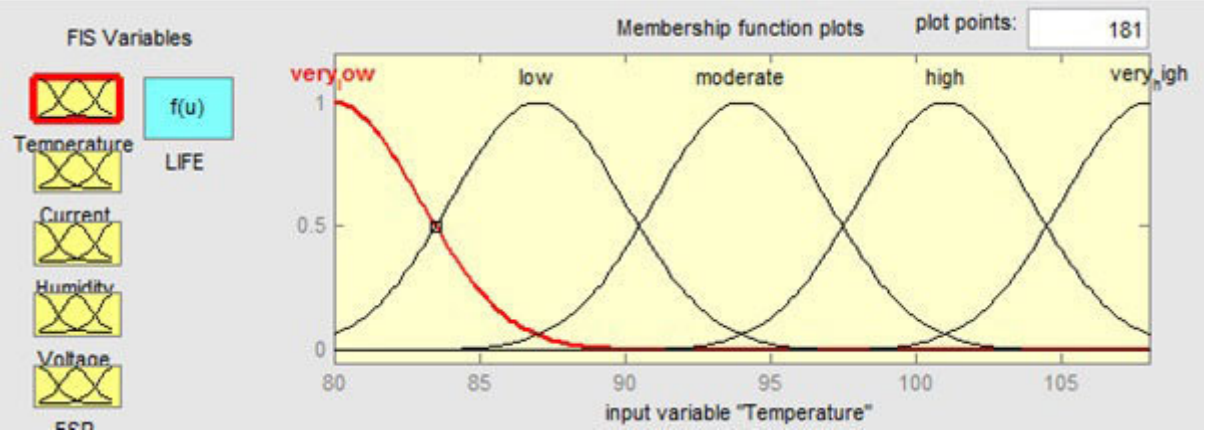


Figure 4.15: *Gaussian membership function used for input variable" Temperature"*

Figure 4.15 shows the membership function plots for temperature as input variable and life as the output variable.

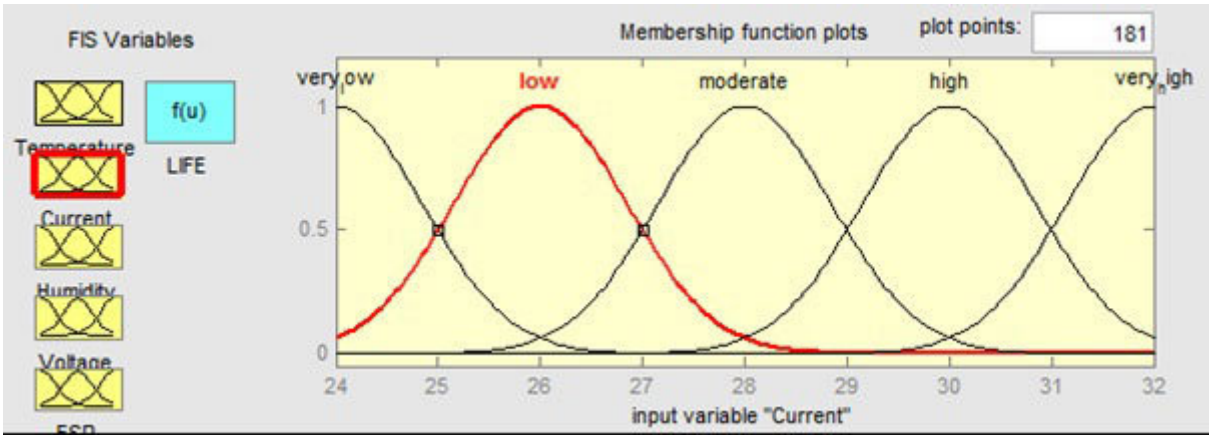


Figure 4.16: *Gaussian membership function used for input variable "current"*

Figure 4.16 shows the membership function plots for ripple current as input variable and life as the output variable.

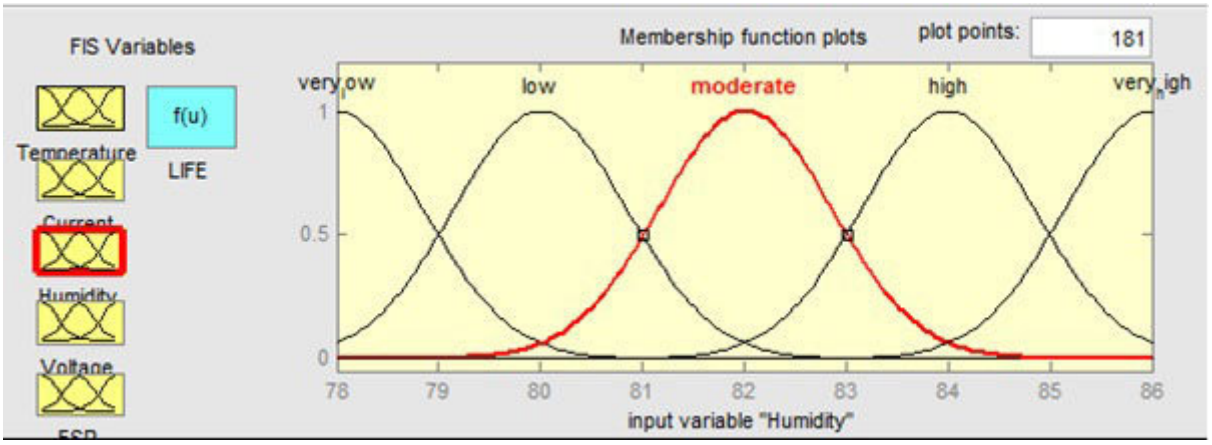


Figure 4.17: *Gaussian membership function used for input variable" humidity"*

Figure 4.17 shows the membership function plots for humidity as input variable and life as the output variable.

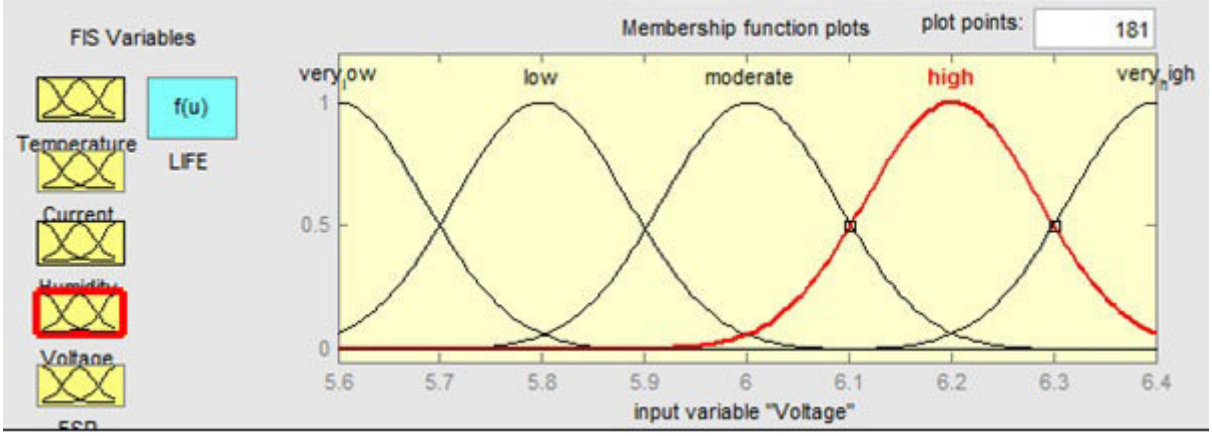


Figure 4.18: *Gaussian membership function used for input variable" voltage"*

Figure 4.18 shows the membership function plots for voltage as input variable and life as the output variable.

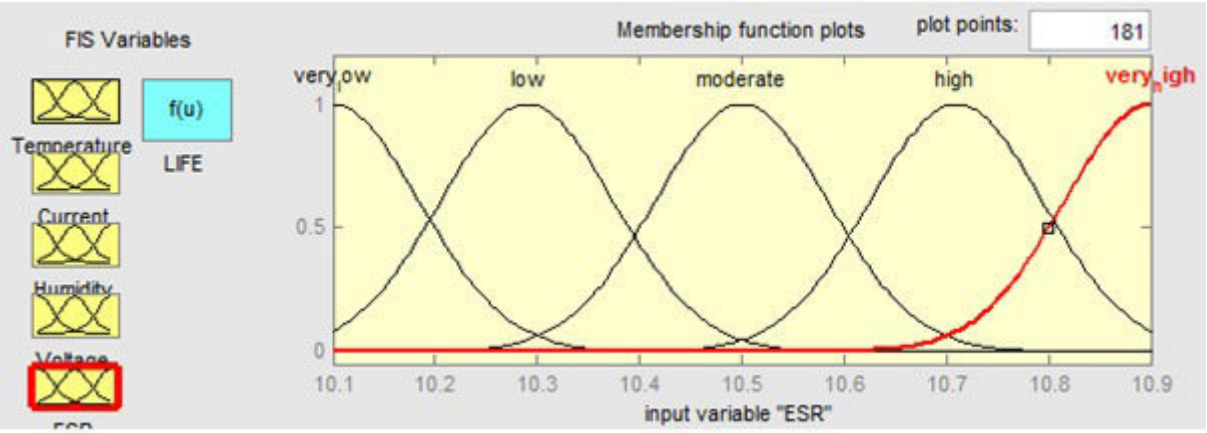


Figure 4.19: *Gaussian membership function used for input variable" ESR"*

Figure 4.19 shows the membership function plots for ESR as input variable and life as the output variable.

After creating various membership functions, rules are generated, which are based upon the input and output variables. In rule viewer, the output values can be explored for different set of input values.

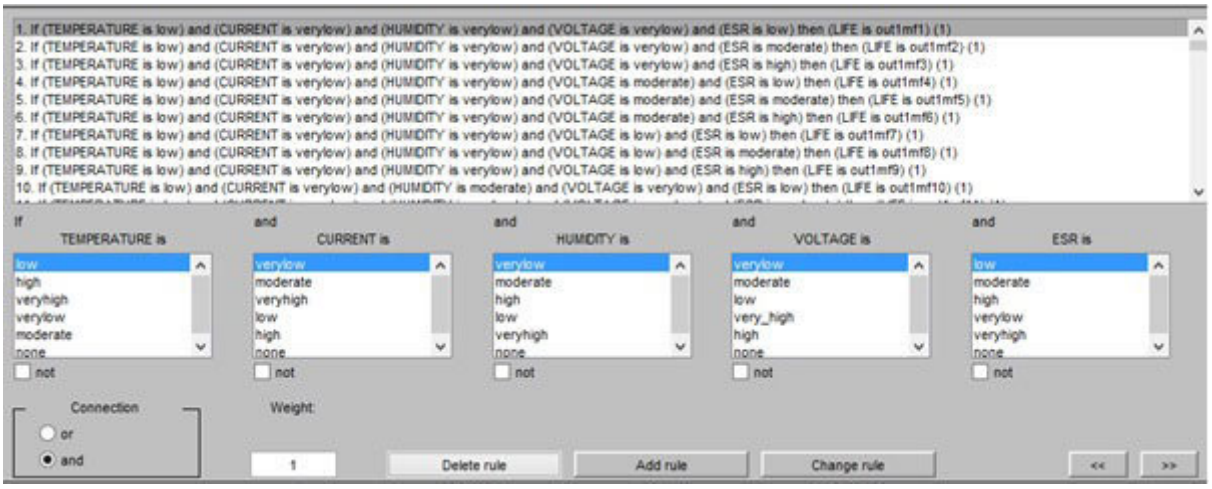


Figure 4.20: *Rules applied to Sugeno fuzzy system*

The various fuzzy rules used in sugeno fuzzy system are shown in *figure*

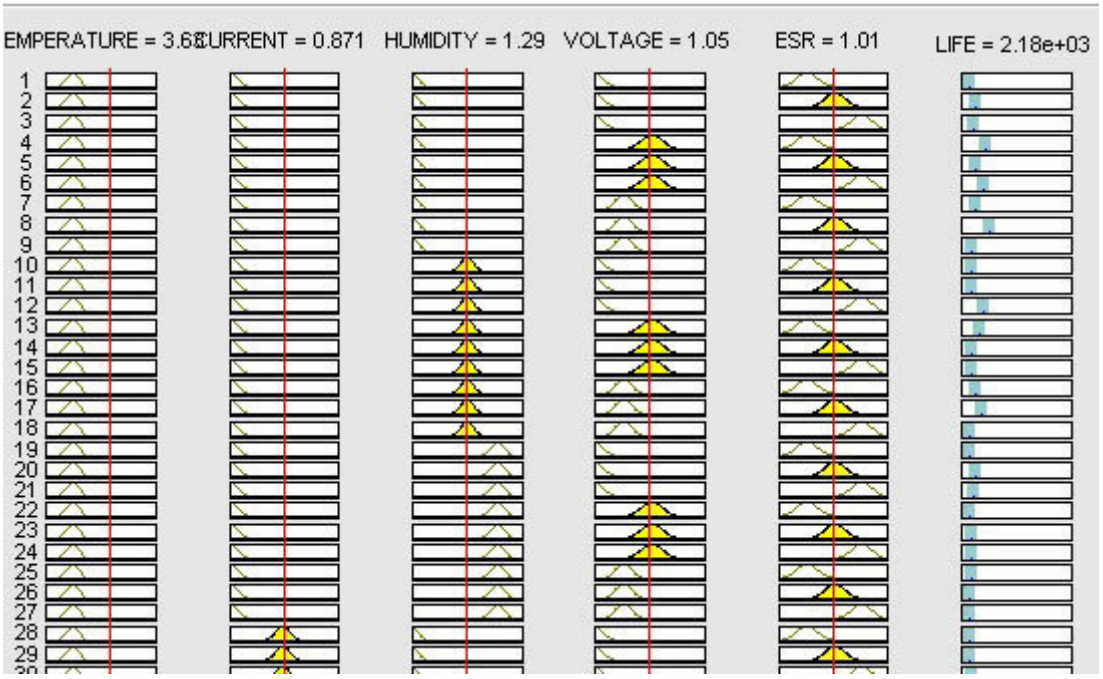


Figure 4.21: *Rule viewer of ANFIS model*

The range and categorisation of process variables are explored in *table 4.4* and their linguistic interpretation is analysed.

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Table 4.4: *Neuro-fuzzy input coded form*

Then, the output, i.e., life is divided into appropriate levels, starting from minimum to maximum. The linguistic interpretation of specified range is designated as very low (VL), low (L), moderate (M), high (H), and very high (VH).

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Table 4.5: *Fuzzy output coded form*

So, neuro-fuzzy system is used to predict the failure of electrolytic capacitor. The linguistic coded form is further interpreted using decision support system.

Decision Support System

The **decision support system (DSSRL)** is an interactive approach, which interacts with the user or consumer and enables the decision-making capability using graphical user interface. This technique is useful to analyse and interpret the health status of the component. The replacement of the faulty component can be done well before the complete shutdown of the process due to the faulty product or component. A fuzzy logic-based decision support system is exhibited for evaluation and interpretation of the proposed analytical model. *Figure 4.22* depicts the flow chart of DSSRL (decision support system for residual life) of specific component. This section explores the development process of the decision support system.

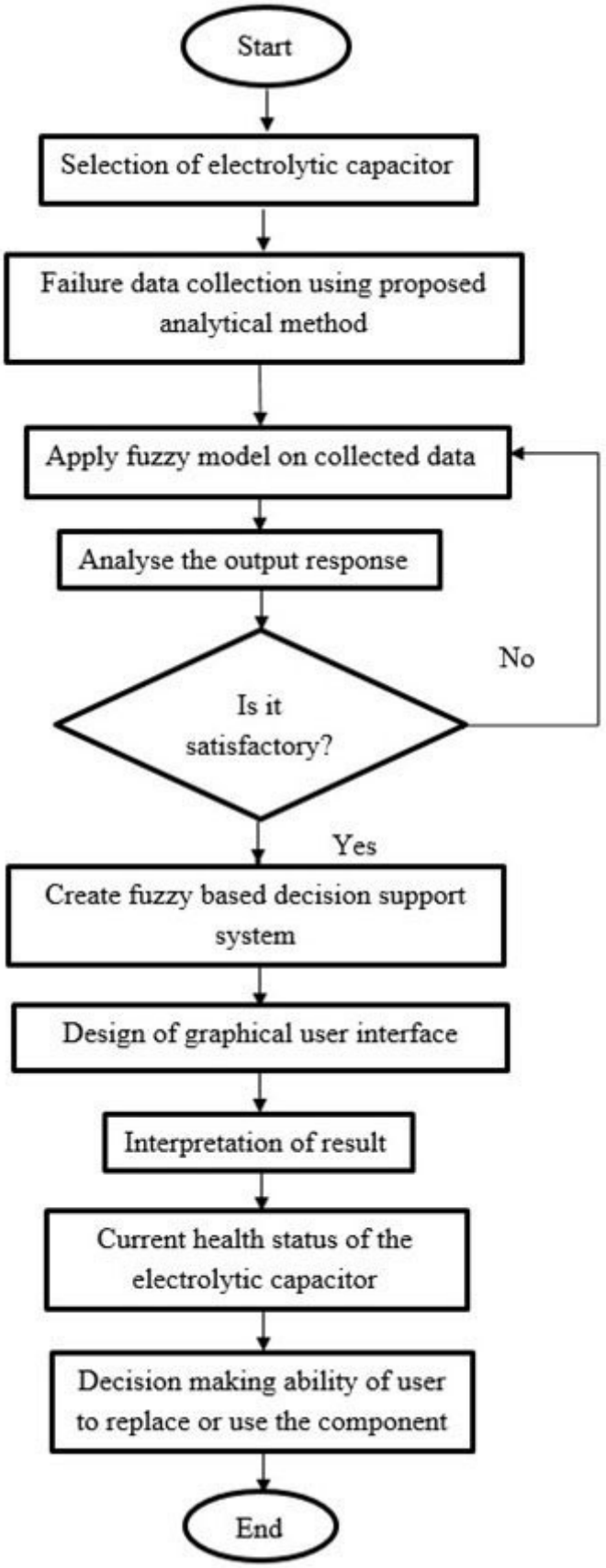


Figure 4.22: *Flow chart of decision support system*

This DSSRL system is developed using the MATLAB R2013a software. The overall classification is done using the fuzzy logic toolbox. The GUI provides the communication between the user and system[15]. GUI is also called the graphical display in one or two windows containing the different parts called components[16]. The components contain the push button, static text, edit text, popup menu, slider, etc. The graphical user interface shows the critical parameters. In this GUI, the user will fill the input details, i.e., values of temperature, current, humidity, voltage, and ESR. After clicking on the push button, the system will interact with the user by displaying the residual life. The user will interpret the results and carry out the necessary replacements, if needed.

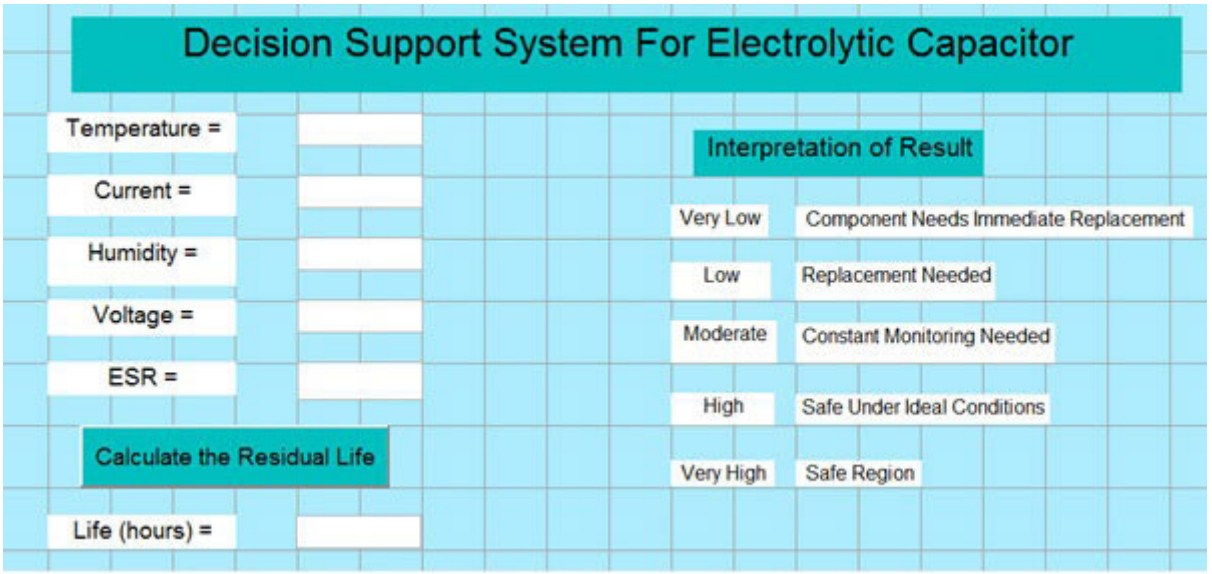


Figure 4.23: *Decision support system for electrolytic capacitor*

So, the decision support system is an interactive approach to evaluate the quality performance of proposed analytical method, as well as to empower the user to act accordingly, for the successful operation of the complete system.

Case study of electrolytic capacitor

An **electrolytic capacitor** is one of the prominent passive components, which is used in all electronic devices and circuits. The capacitor failure can lead to destruction of human life. In the following section, the residual lifetime of electrolytic capacitor is calculated using various methods.

Calculation of lifetime using neural networks

Using ANN approach, lifetime (hours) value of electrolytic capacitor has been predicted as per *table* It has been analysed that maximum lifetime is achieved as 14949.74 hours, when temperature is 80° C, ripple current is 24 milliampere, humidity is 78 %Rh, voltage is 5.6 volts, and ESR is 10.1 ohms.

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Table 4.6: *Lifetime prediction of electrolytic capacitor using ANN method*

Training fuzzy logic model

The fuzzy model for electronic component residual lifetime prediction is also trained using MATLAB fuzzy tool box. Here, the network is trained with 70% of the measured data. Fifteen percentage of the data is used for testing, and the other 15% of the data is used for validation. The fuzzy model is validated by conducting prediction accuracy test using percentage error. The percentage error of each prediction is used to determine the effectiveness of the fuzzy model. It is calculated using the equation.

The fuzzy logic is an approach of computing, which is based on the degrees of truth. In fuzzy logic modelling, 25 trial datasets have been considered, out of which 17 dataset values are taken for training purpose, 4 datasets for testing, and 4 datasets for validation.

Calculation of electrolytic capacitor lifetime using fuzzy logic model

Using fuzzy logic approach, lifetime (hours) value of electrolytic capacitor has been predicted, as per *table* It has been analysed that maximum lifetime is achieved as 14960.16 hours, when temperature is 80° C, ripple current is 24 milliampere, humidity is 78% Rh, voltage is 5.6 volts, and ESR is 10.1 ohms.

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Table 4.7: *Lifetime prediction of electrolytic capacitor using Fuzzy logic method*

Failure prediction using adaptive neuro-fuzzy inference system model

An adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference system. As discussed earlier, the ANFIS model for tool life prediction is also trained using MATLAB fuzzy tool box. Here, the network is trained with 70% of the measured data. Fifteen percentage of the data is used for testing, and the other 15% of the data is used for validation. The predicted values of the ANFIS model are given in *Table* For lifetime prediction of electrolytic capacitor, using ANFIS model 25 trial dataset has been considered, out of which 17 dataset values are taken for training purpose, 4 dataset for testing, and 4 dataset for validation.

Lifetime calculation of electrolytic capacitor using ANFIS model

Using ANFIS approach, lifetime (hours) value of electrolytic capacitor has been predicted, as per *table* It has been analysed that maximum lifetime is achieved as 14978.23 hours, when temperature is 80° C, ripple current is 24 milliampere, humidity is 78% Rh, voltage is 5.6 volts, and ESR is 10.1 ohms.

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Table 4.8: *Lifetime prediction of electrolytic capacitor using ANFIS method*

It has been analysed that out of four prediction models, i.e., regression, artificial neural networks, fuzzy logic, and ANFIS approach, the prediction accuracy of ANFIS approach comes out to be the maximum, i.e., 99.28%. The comparison of these prediction model responses, on the basis of error analysis, is shown in the following screenshot:

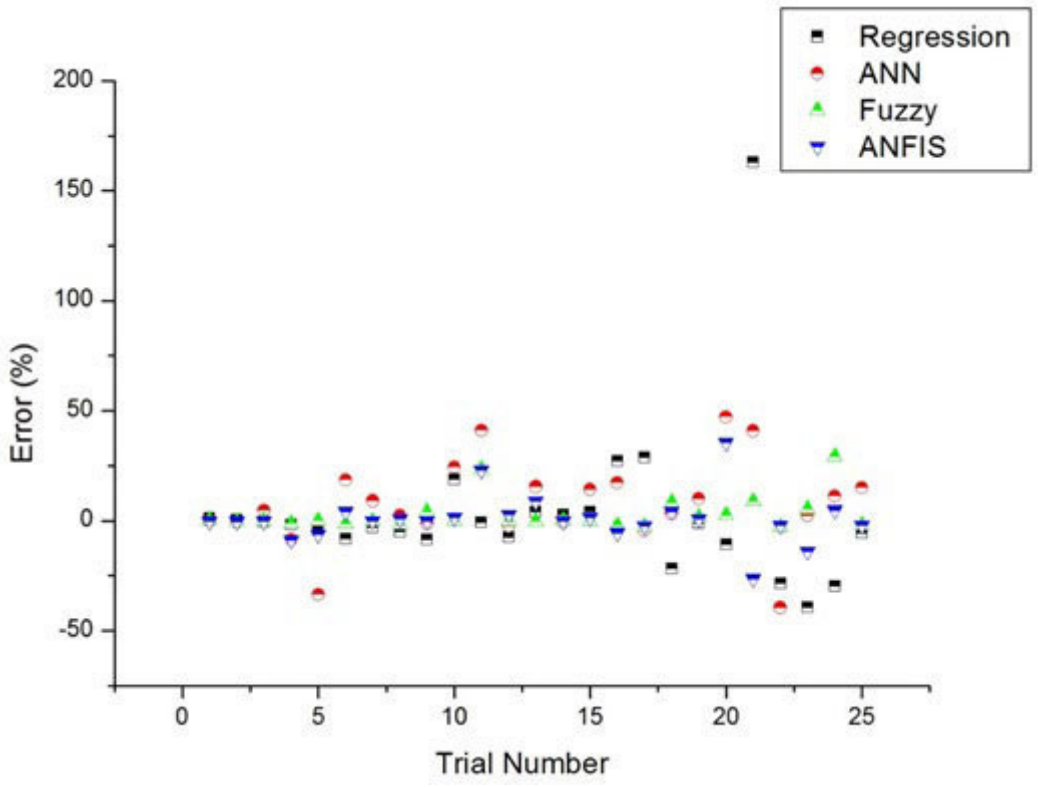


Figure 4.24: *Comparison of lifetime prediction techniques for electrolytic capacitor*

Conclusion

In this chapter, various methods of artificial intelligence are incorporated to predict the residual lifetime of electrolytic capacitor. The case study of electrolytic capacitor is demonstrated with the help of ANN, Fuzzy logic, and ANFIS. The accuracy of all the techniques is explored and best method is chosen for residual lifetime prediction. The graphical user interface is discussed and designed with the help of fuzzy logic.

Questions

How can the intelligent modelling of electronic components be done?

What is the significance of Artificial Intelligence Techniques for RUL prediction?

Differentiate between ANFIS and ANN, using reliability analysis example.

Differentiate between ANFIS and Fuzzy Logic, using reliability analysis example.

What do you mean by GUI? How it is formed, and what is its use?

How can the most accurate system be assessed?

CHAPTER 5

Accelerated Life Testing

Introduction

The failure time of an electronic component is predicted accurately using the experimental technique. Since it is difficult to put a component on continuous testing for many hours together, therefore, the accelerated life testing methodology is adopted.

Structure

In this chapter, we will discuss the following topics:

Experimental techniques

Acceleration factors

Accelerating life testing

Arrhenius equation

Remaining Useful Life (RUL) assessment

Objectives

After studying this chapter, the students should be able to use the experimental technique for the reliability prediction, conduct the accelerated life testing and the residual life prediction, and calculate the MTBF and FIT in terms of the remaining useful lifetime.

Importance of accelerated life testing

In this technique, the component or the sample is placed under the accelerated stress parameters for a few hours. For example, a Sterile barrier system that is subjected to 40 days of accelerated aging at +55° C has the similar aging characteristics as a 1-year-old real time sample. So, the accelerated aging test data is acceptable to most of the regularity's bodies. For the accelerated life testing, 30 electrolytic capacitors have been selected. They have been put under the accelerated stress continuously for 240 hours. The design of the experiments using the Taguchi approach is adopted to minimise the total number of experiments. Similarly, the humidity sensor is testing under the accelerated life testing approach. The Arrhenius method is used to analyse the response of the accelerated life testing.

Experimental approach for the failure prediction of the electrolytic capacitor

To explore the residual lifetime or predict the failure of an electrolytic capacitor, a real-time testing has been conducted on the electrolytic capacitors, which is known as the **accelerated life** where the accelerated values of the evaluation parameters are provided to explore the remaining useful lifetime. As it is a very tedious job to conduct the experiments for all the variables, for long hours, the **design of experiment** technique is used to design the input parameters of the experiment.

Materials and methods

To conduct the accelerated life testing, an electrolytic capacitor was chosen and its rated parametric values were noted as per its datasheet. The total 30 units of these capacitors were taken, where each capacitor is drilled with a 9-mm hole. Initially, all the 30 capacitors were analysed using the LCR meter and the initial readings were noted for the capacitance, ESR and weight of each capacitor. A digital hot plate was taken as a source of thermal stress. The electrolytic capacitors were covered with the sand, so that these capacitors would be uniformly heated. The specifications of the selected electrolytic capacitor are shown in *Table*

Table 5.1: *Electrolytic capacitor specifications*

The accelerated values of the input parameters were decided as per the rated specification indicated in the datasheet.

Determination of the experimental parameters: A DOE approach

The **Taguchi approach** is a systematic means of designing, conducting, and analysing the experiments which are of great significance in the quality planning. The experiments are conducted based on the Taguchi approach and the tool life values obtained. The use of the Taguchi approach leads to a significant economic advantage by resulting in the reduction of the material and the machining time required for the expedition due to the reduced set of experiments. The steps in designing, conducting, and analysing the experiments are as follows:

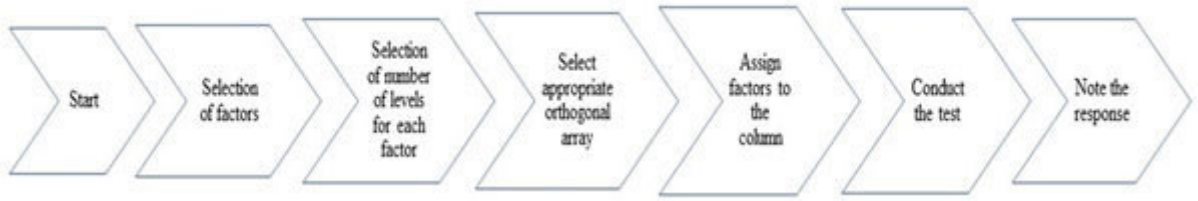


Figure 5.1: *Taguchi approach for DOE*

For the design of the experiments, the Taguchi approach is selected. This approach consists of the following steps:

Selection of the factors for the study

Selection of the number of levels for the factors

Selection of the appropriate orthogonal array

Assignment of the factors to the columns

Conduct of the test

Selection of the factors for the study

In this research work, the temperature, ripple current, humidity, voltage, and ESR are selected as the factors to carry out the experimental work, and for the subsequent development of a mathematical model.

Selection of the number of levels for the factors

In order to develop the capacitor residual life prediction model, five factors at five levels each are selected. The selected process parameter for the experiment with their limits, units, and notations are given in *table*

Table 5.2: *Process variables and limits*

Selection of the appropriate orthogonal array

The standard L25 orthogonal array is shown in *Table* The columns 2, 3, 4, 5, and 6 from the standard table are selected for obtaining all the combination of the five process parameters. This is the Taguchi design. It is designed using the Minitab 8.1 software, using the 25 different combinations of the process parameters with their limits.

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Table 5.3: *L25 Orthogonal array*

Table 5.4 is formed while assigning the variables in the linguistic form: very low (VL), low (L), moderate (M), high (H), and very high (VH).

Assignment of the factors to the columns

The selected standard table in the coded form and the actual form are presented in a design matrix in *Table* The experiments are conducted for all the possible combinations of the parameter levels. The combinations are written in the form of a design matrix, where the rows correspond to the different trials and the columns to the different levels of the parameters.

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Table 5.4: *Linguistic assignment of process variables*

After assigning the linguistic variables to the factors, the actual values of the factors for all the process variables are assigned to the Taguchi L25 orthogonal array. This is summarised in *Table* The trial number indicates the number of experiments performed as per the values of the process variables. This is the design of the experiments for the electrolytic capacitors using the Taguchi approach.

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Table 5.5: *Actual form of the process variables*

Conduct of the test

After designing the experiments using the Taguchi approach, 25 trials were suggested. Each trail consisted of 30 units of the electrolytic capacitors, as per the specification mentioned in *table* The initial reading using the LCR meter was taken, after which a hole of 9 mm was drilled in each capacitor, which were then placed on a hot plate, covered with sand, so that there would be uniform heating. The used digital hot plate is shown in the following screenshot. The input parameters were selected as per the trail suggested by the Taguchi approach.



Figure 5.2: *Digital hot plate*

Here, the accelerated temperature was set as 108° C and the ambient temperature was chosen as 45° C. At the start of the

experiment, the capacitors were placed at the ambient temperature on the hot plate. Gradually, the temperature was increased up to 108° C (Ta=15 minutes). The thermal profile is shown in the following figure:

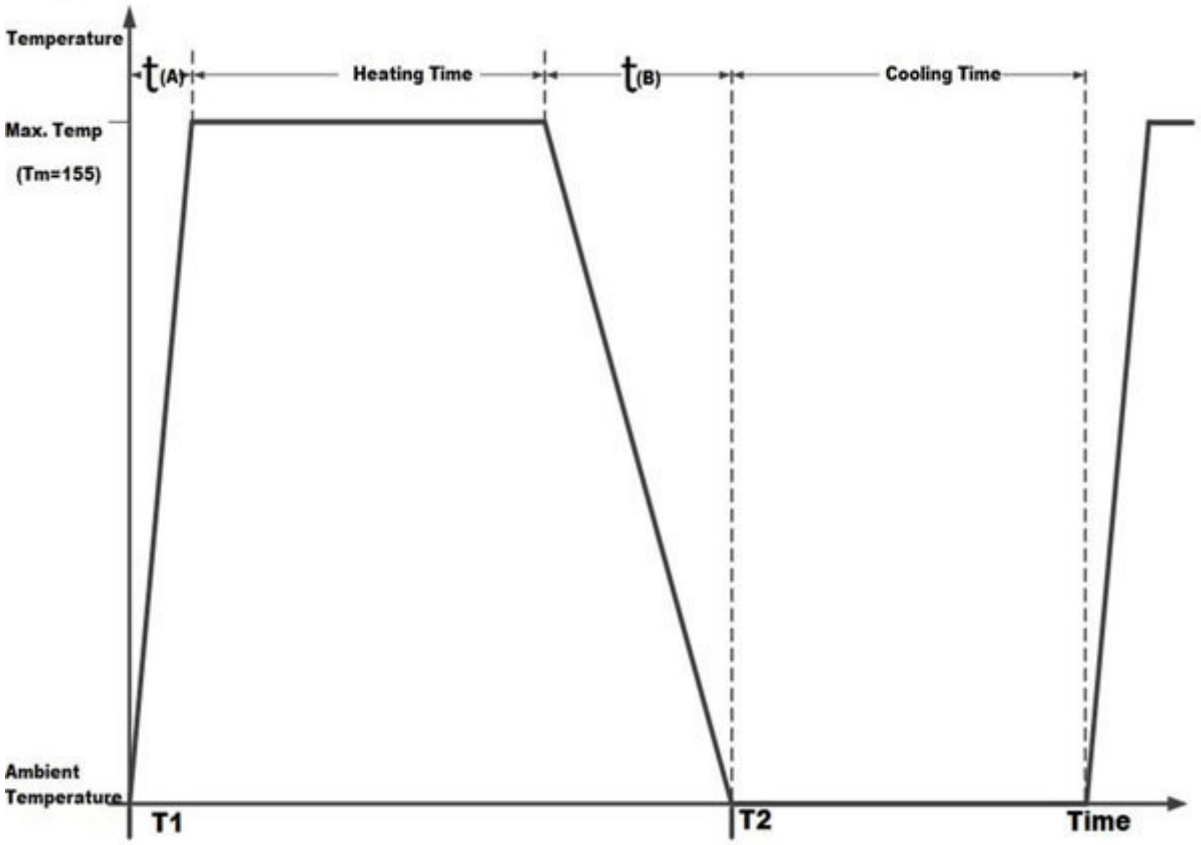


Figure 5.3: *Accelerated testing time versus temperature*

At the end, T1 and T2 times, the values of the capacitance, ESR, and the weight loss were measured again. The failure time was calculated as the failure conditions. To check the failure of an electrolytic capacitor, the following three conditions were considered:

If the capacitance decreases by 20%.

If the ESR increases by 100%.

If the weight decreases by half.

As the temperature rises, the electrolyte of the capacitors will evaporate. With the evaporation of the electrolyte, the capacitance decreases and the ESR increases. The reduction in the weight is an indicator of the electrolyte loss.

Analysis of the failure time

During the experiment, the response of the accelerated life testing was noted. The failure in time (FIT per hours) and the mean time between failure (MTBF) were calculated using the Arrhenius equation of the acceleration factor. To decide the failure status of the capacitor, the three previously mentioned conditions should be satisfied.

$$FIT\ (\lambda) = \frac{F}{D \times T \times Af}$$

Here,

F=Number of failures; D=Number of devices tested; T=Test hours.

Ea=Activation energy (ev)=0.7eV

K=Boltzmann constant

temperature; temperature.

After calculating the failure rate, the mean time between failures (MTBF) corresponding to the failure rate (FIT) was calculated as follows:

$$MTBF(hours) = \frac{1}{\lambda} \times 10^9 \text{ hours}$$

$$MTBF(years) = \frac{MTBF(hours)}{24 \times 365}$$

The failure rate and the corresponding MTBF data have been analysed. It reflects the inverse relationship between reliability and temperature.

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Table 5.6: *Calculation of the residual lifetime using the experimental approach*

Analytical approach for the failure prediction of the electrolytic capacitor

As discussed in *previous chapter,* a technique was proposed using the mathematical/analytical model, which predicts the failure or the residual life of an electrolytic capacitor by considering the acceleration factors of all the influencing parameters, as per equation 5.6, 5.7 and 5.8.

By considering the previously mentioned acceleration factors, de-rated lifetime, or residual life of an electrolytic capacitor is calculated as follows:

$$Lifetime\,(E) = Lifetime(D) \times Acceleration\,factor \tag{5.6}$$

It can also be written as follows:

$$Lifetime\,(Expected) = Lifetime(D)\ \times At \times Av \times Ar \times Ae \times Ah \tag{5.7}$$

So, the expected lifetime or residual life can be concluded, by putting the values of the acceleration factors from the equation (4.1) to (4.5), into equation (4.7)

$$Lifetime\,(E) = Lifetime(D) \times\ 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \times Ki^{A\frac{\Delta T}{10K}} \times \frac{\sqrt{ESR(fo)}}{\sqrt{ESR(fa)}} \times \exp\{C \times ((RHa)^n - (RHm)^n)\} \tag{5.8}$$

Here, the expected lifetime [Lifetime (E)] and datasheet life [Lifetime(D)], both are specified in hours.

The equation (4.8) represents the expected lifetime (hours) for an electrolytic capacitor, when the operating conditions of the electrolytic capacitor are different from the maximum rated conditions, specified in the datasheet.

By using this proposed equation, the failure of the electrolytic capacitor is analysed and summarised, as shown in *table*

Table 5.7: *Calculation of residual lifetime using proposed analytical approach*

Error analysis of the analytical failure prediction model of an electrolytic capacitor

By comparing the calculated failure time or residual lifetime using the analytical method with the failure time calculated using the experimental lifetime, the error can be calculated as per the following equation:

$$Error\ (\%) = \frac{Experimental\ value - Analytical\ value}{Experimental\ value} \times 100$$

The error analysis of the failure prediction models is summarised in *Table*



Table 5.8: *Error analysis of experimental and proposed analytical technique*

So, the average accuracy of the proposed analytical model using the Taguchi approach of the DOE technique is 96.75%, which validates the proposed model for the failure prediction of the electrolytic capacitors. The graphical representation of the residual lifetime calculated by the experimental method and the proposed analytical method is shown in *figure* It represents th proposed analytical technique is successfully opted as the failure prediction technique of the electrolytic capacitors.

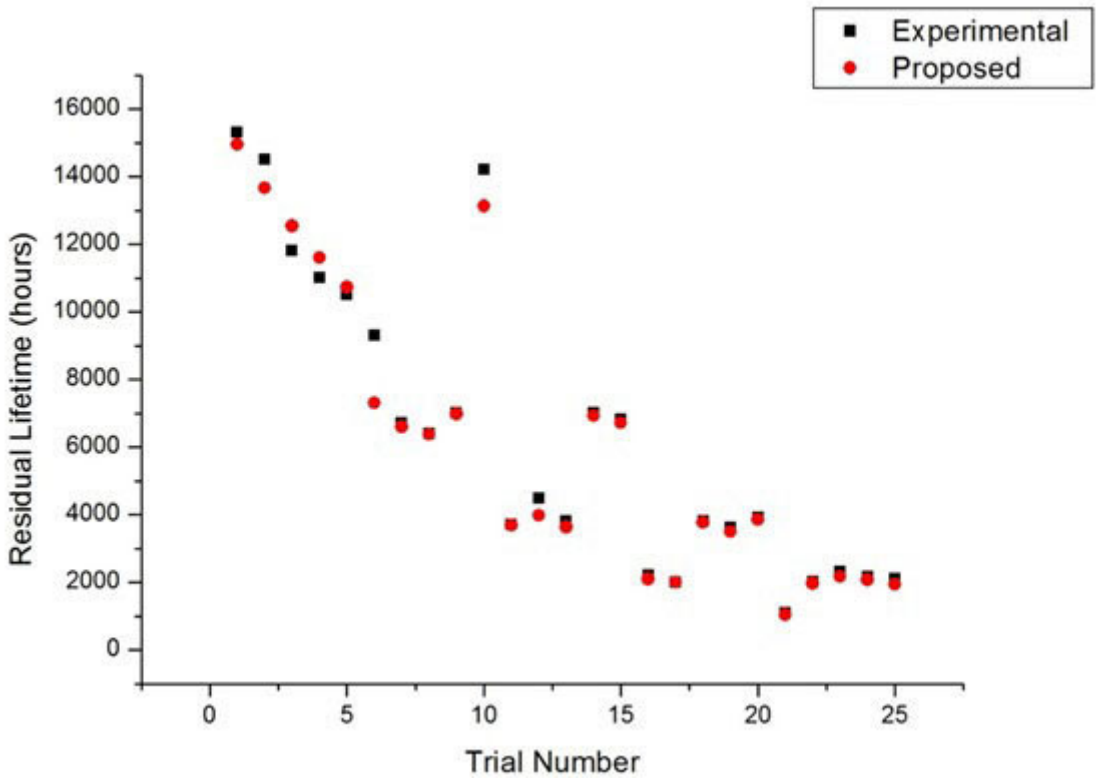


Figure 5.4: *Response of experimental versus proposed analytical method*

Experimental approach for the failure prediction of the humidity sensor

A Humidity sensor detects, measures, and reports the content of moisture in the air. The presence of water vapour in the air is called If humidity exceeds by a particular level, it can cause problems to the respiratory systems, skin, as well as the eyes. It also enhances the electrostatic discharge from the body to the conductive surface. The accurate humidity sensor can prevent the products to be corroded and spoiled. In this research work, a humidity sensor has been fabricated using low cost composite materials, i.e., carbon black and potash alum. Then, the various characterisation techniques are used to verify the composite nature of the humidity sensor.

Failure prediction of the humidity sensor

Reliability is one of the major challenges that a sensor technology faces. To predict the failure of a sensor before their time, can save the entire system. The failure can be predicted using the FIT (failure in time) and the MTBF (mean time between failures).

The 25 units of the maximum ionic conducting samples were prepared, which acted as a good humidity sensor. To predict their failure and the remaining useful life, these 25 units were kept under different temperature conditions for 240 hours. It showed that a few units could not bear the high temperature for a fixed time. The results of these accelerated life test were recorded. The failure in time (FIT per 109 hours) was calculated using the Arrhenius equation of the acceleration factor. The Arrhenius equation for the failure calculation is as follows:

$$FIT\ (\lambda) = \frac{F}{D \times T \times Af}$$

Here,

F=Number of failures; D=Number of devices tested; T=Test hours.

factor;

Ea=Activation energy (ev)=0.7eV

K=Boltzmann constant

temperature; temperature.

After calculating the failure rate, the mean time between failures (MTBF) corresponding to the failure rate (FIT) was calculated as follows:

$$MTBF(hours) = \frac{1}{\lambda} \times 10^9 \text{ hours}$$

$$MTBF(years) = \frac{MTBF(hours)}{24 \times 365}$$

The digital hot plate was used to provide the thermal stress. A total of 17 trials were conducted at different temperatures. The failure or the residual lifetime of the humidity sensor was measured using the Arrhenius equation. The response of the accelerated life testing is summarised in *table*

Table 5.9: *Failure time calculation of humidity sensor*

The failure in time (FIT) and the mean time between failure (MTBF) are calculated using the Arrhenius law. It has been analysed that as the temperature increases, the remaining useful lifetime of the humidity sensor decreases. This has been graphically demonstrated in *figure* which proves the inverse relationship of the temperature and the residual lifetime of a humidity sensor.

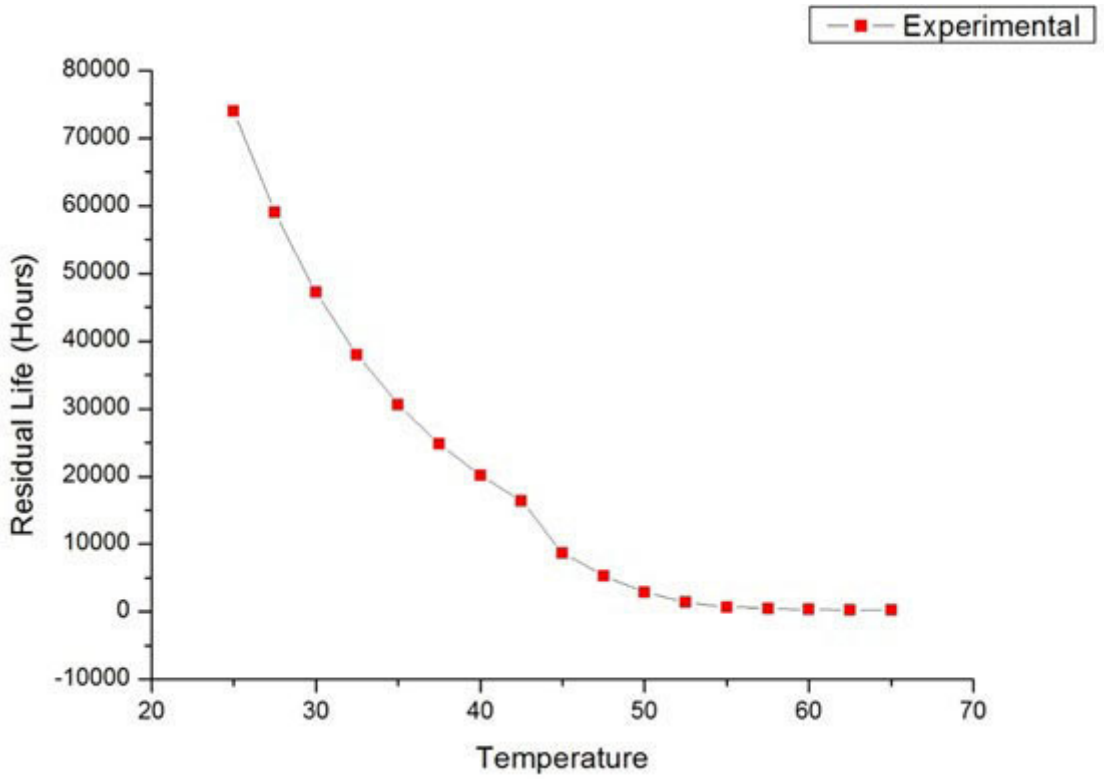


Figure 5.5: *Temperature versus residual life of humidity sensor*

So, using the experimental techniques of the real time failure data of the electronic components, such as the electrolytic capacitor and the humidity sensor, has been explored and analysed. Here,

the Taguchi approach allows us to determine the required data (response values) with a minimum set of experiments. The details of the experimental setup for the failure time or residual lifetime determination are discussed. The steps involved in the determination of the experimental value, determination of the actual lifetime, and the analysis of the error for the various prediction models of the electrolytic capacitors, under the various process parametric conditions are detailed.

Conclusion

This chapter highlights the need for the experimental techniques for the reliability prediction. The process of the accelerated life testing is well understood by the example and MTBF, FIT etc. are calculated, which further confirms the accuracy of the reliability prediction system. The failure prediction and the regression analysis is conducted using the example of the electrolytic capacitor.

In the next chapter, the incorporation of the experimental techniques has been done, which estimates the upcoming failure and warns the user of the active and passive components, so that the necessary replacement of the faulty components can be done well before time.

Questions

What do you mean by the following:

MTBF

FIT

How are MTBF and FIT co-related?

How does the residual life of a component matters the performance of a device?

How will you measure that the capacitor is a failure or is faulty during the experimental process?

If the failure in time for the capacitor is hours, then calculate the MTBF and the MTTR?

CHAPTER 6

Experimental Testing of Active and Passive Components

When a manufacturer releases a component in the market, a datasheet is provided along with it. The datasheet has all the input parameters with a specified range, as well as the performance parameters of the component. But, when it is used in a real life application, the environmental conditions may vary, which can break down the component, and automatically shut down the complete system.

Structure

In this chapter, we will discuss the following topics:

Reliability analysis of the active and passive components

Accelerated life testing

Calculation of FIT, MTBF and reliability

Experimental setup

Environmental conditions for the experiment

Objectives

After studying this chapter, the students should be able to understand the need for reliability prediction in active and passive components, learn about the experimental technique for the reliability production, and know the step-wise procedure and the experimental details for the failure prediction.

Accuracy estimation and error analysis

With the rapid evolution of the electronics device technology towards low cost and high performance, the electronics products become more complex, higher in density and speed, and lighter for easy portability. The electronic packaging engineers are integrating more and more chips and parts into the assembly. As the electronics industry has enhanced towards the miniaturization and increasing functionality, the use of green materials, and the trends toward the heterogeneous systems based on the **system in chip system in package** or **system on package** has also increased. In today's competitive market, all the manufacturers need to increase performance and reduce the cost of their products, so that the customers get more attracted towards their products. The growing system complexity demands robust control to mitigate the system control and disturbances. The reliability aspects are of extreme importance for the assembly and packaging, which has become a limiting factor for both the cost and the performance of the electronic systems.

As an electronic component or device is implanted in the real world applications, several factors affect its performance, as well as reliability. The failure prediction or the residual life estimation becomes a mandatory aspect for the successful operation of the electronic component or device. The lifetime claimed by the manufacturer, as per the datasheet can be varied, depending on the environmental conditions and the electrical parameters.

Sometimes, these components or devices are quite often discarded without being used it to its full potential. Such discarded components are found to have some remaining useful life left. Considering these aspects, here an attempt is being made to assess the reuse potential of the used components. Predicting the remaining useful life is a step toward identifying the reuse potential. The following steps play a vital role in the assessment of the remaining useful life of the electronic component:

The methodology used to arrive at the reuse potential of the electronic component,

The simplicity of the methodologies/techniques used for the analysis, and

The capability of the models developed for an accurate prediction.

With this end in view, here, a comprehensive methodology is developed for the failure prediction, which is based on the residual lifetime left, for a specific component or device.

In order to operate the electronic device efficiently and fault free, the reliability of that component is calculated in the elevated environmental conditions, so that the user can be warned well before the **end of life** of the component.

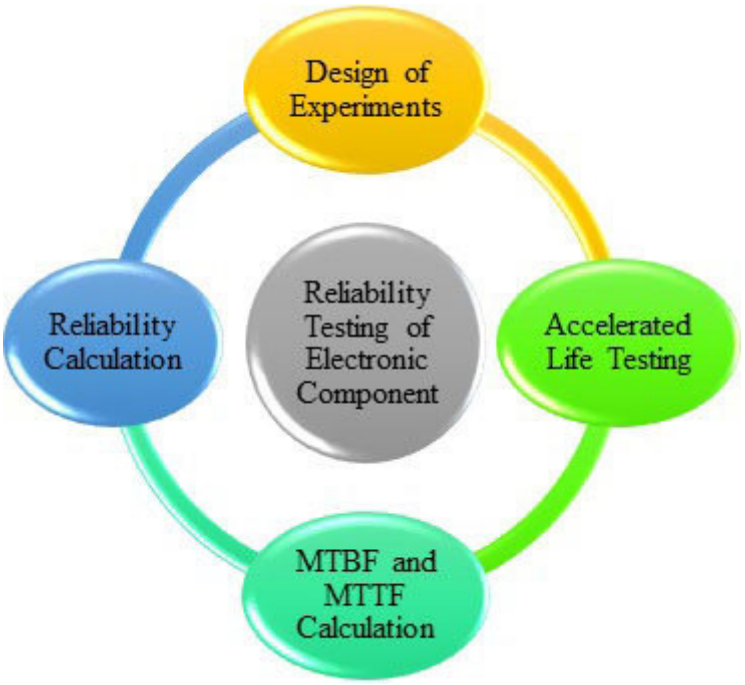


Figure 6.1: *Reliability Testing of Electronic Components*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and total number of components, as per the following equation (i):

$$MTBF = \frac{Total\ time\ of\ experiment}{Number\ of\ failures} \quad \text{(i)}$$

The mean time to failure (MTTF) can be calculated using the following equation (ii), which interrelates the total number of components and the time taken by the whole experimental process.

$$MTTF = \frac{Total\ time\ of\ experiment}{Number\ of\ components\ under\ test} \quad \text{(ii)}$$

The failure rate and the mean time to failure have an inverse relationship, as per the following equation (iii):

$$Failure\ rate\ (\lambda) = \frac{1}{MTBF} Failure\ rate\ (\lambda) = \frac{1}{MTBF} \quad \text{(iii)}$$

The reliability can be calculated further, by considering the number of failures and the total experimental time. It is calculated as per the following equation (iv):

$$Reliability\ R(t) = e^{-\lambda t} \quad \text{(iv)}$$

The reliability of the components tells the consistency of the performance of the previously said component in an elevated thermal environment.

Evaluation of the reliability of the humidity sensor DHT11

The **humidity sensor** is used in various applications, for example, the lie detector, soil or dew measurement, the environmental condition monitoring etc. In this practical, a DHT11 is used as a humidity sensor. The reliability of the humidity sensor DHT11 is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The DHT11 and the digital hot plate are shown in the following *figure 6.2(a)* and *figure 6.2(b)* for reference.

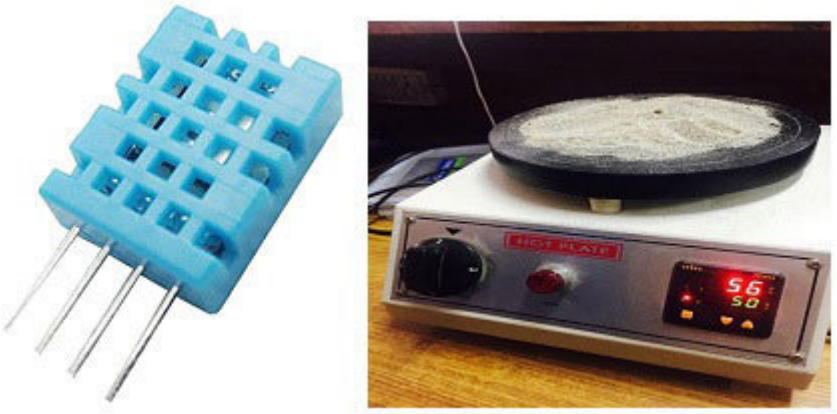


Figure 6.2: *(a) DHT11 Humidity Sensor (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to time and the total number of components.

The reliability of the components tells the consistency of the performance of the previously said component in an elevated thermal environment.

Procedure for the experimental testing of the humidity sensor

The following steps should be followed, with the prescribed precautions to analyse the reliability and assess the remaining useful lifetime of the components:

Choose the 100-150 samples of the humidity sensor DHT11.

Verify whether all the components are working properly.

Explore the datasheet of DHT11 and the stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, 0-50-degree Celsius in case of DHT11.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand so that uniform heating can be provided and then put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and maximum temperature range as 60 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per the equation (i-iv).

Draw the graph between MTBF and Reliability.

Evaluation of the reliability of temperature sensor LM35

The **temperature sensor** is widely used in the industry and in automation. The use of the temperature sensor is from home to hospital and from toy to satellite. It is the base for many critical applications. For the successful operation of an electronic device, the reliability analysis of the temperature sensor is an important factor. The reliability of the temperature sensor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The LM35 and the digital hot plate are shown in the following *figure 6.3(a)* and *figure 6.3(b)* for reference.

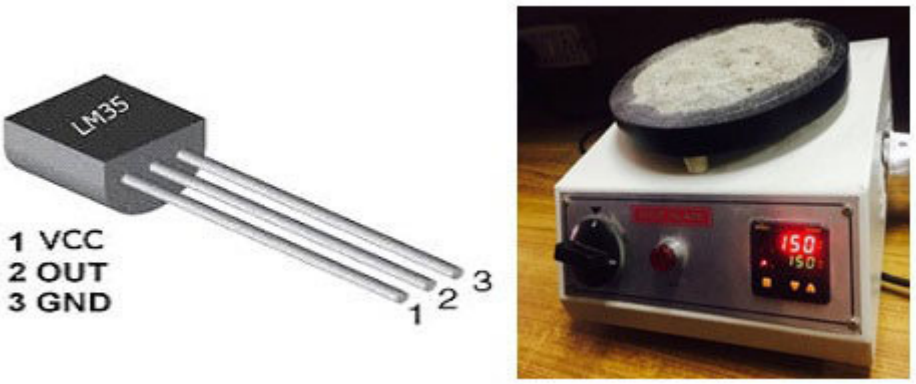


Figure 6.3: *(a) LM35 Temperature Sensor (b) Digital hot plate*

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Choose the 100-150 samples of the temperature sensor LM35.

Verify whether all the components are working properly.

Explore the datasheet of the LM35 and the stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -55 to 150 degree Celsius in the case of LM35.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 160 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate and the Reliability as per equation (i-iv).

Plot the graph between MTBF and Reliability.

Evaluation of the reliability of an electrolytic capacitor

For the evaluation of the reliability of an electrolytic capacitor 4700 µf (٢٠٠ Nos.), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required.

When a manufacturer releases a component in the market, a datasheet is provided along with it. The datasheet has all the input parameters with a specified range, as well as the performance parameters of a component. But, when it is used in a real-life application, the environmental conditions may vary, which can break down the component, and automatically shut down the complete system. In order to operate an electronic device efficiently and fault free, the reliability of that component is calculated in elevated environmental conditions, so that the user can be warned well before the end of life (EOL) of the component.

The electrolytic capacitor is a passive component, which is widely used in toy to satellite, automotive industry to military applications. The electrolytic capacitor is the heart of various electronic devices. The reliability of an electrolytic capacitor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The electrolytic capacitor from an Electrobot manufacturer specification 4700 µf, ٢٥ v and digital

hot plate are shown in the following *figure 6.4(a)* and *figure 6.4(b)* for reference:

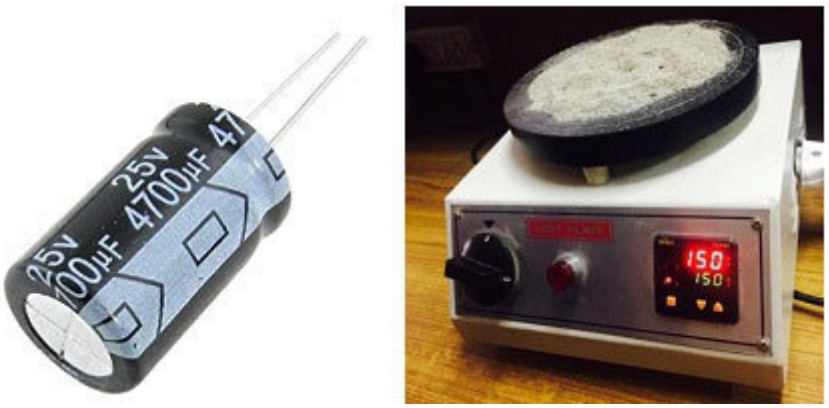


Figure 6.4: *(a) Electrolytic capacitor 4700µf (b) Digital hot plate*

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Choose the 200 samples of the electrolytic capacitor EAN 6971004262647.

Verify whether all the components are working properly.

Explore the datasheet of the electrolytic capacitor and monitor its stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -40 to 85 degree Celsius in the case of EAN 6971004262647, electrolytic capacitor.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 100 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of Carbon Film Resistor

For the evaluation of the reliability of a carbon film resistor 1KΩ serial num 0734130160494 (200 Nos.), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required.

A **carbon film resistor** is a passive component, which is widely used in the industrial, as well as the home automation systems. For the efficient performance of the electronic devices and systems, the reliability assessment of the carbon film resistor has become mandatory. The reliability of a carbon film resistor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The carbon film resistor from an Electrobot manufacturer, serial num 0734130160494 and a digital hot plate are shown in the following *figure 6.5(a)* and *figure 6.5(b)* for reference.

The carbon film resistors are put on the digital hot plate, covered with sand, to analyze the reliability of components:

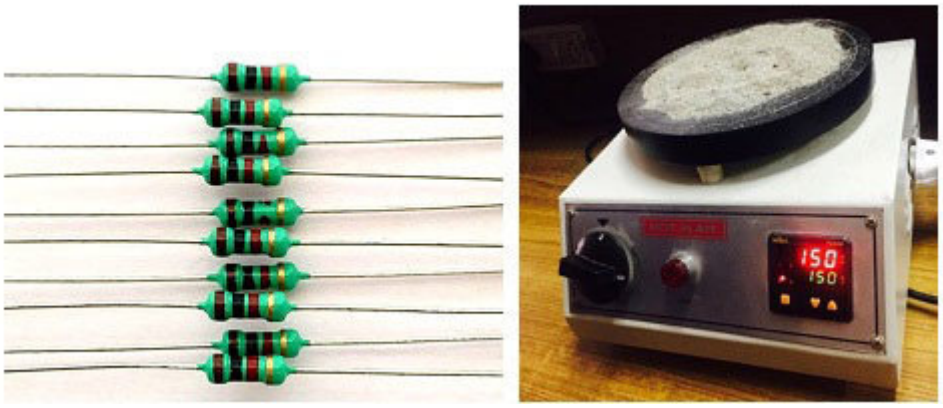


Figure 6.5: *(a) Carbon film resistor 1KΩ (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components, as per the equation.

Procedure for experimental testing

The following steps should be followed, with prescribed precautions, to analyse the reliability and assess the remaining useful lifetime of the components:

Choose the 200 samples of a carbon film resistor from an Electrobot manufacturer, serial num 0734130160494.

Verify whether all the components are working properly.

Explore the datasheet of the carbon film resistor and monitor its stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -55 to 155 degree Celsius, in the case of 1KΩ.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 160 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of PN Junction diode

For the evaluation of the reliability of the PN junction diode IN4007, a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required.

The **PN junction diode** is a passive component which is widely used in the rectifiers, detectors, power supplies etc. The reliability of the PN junction diode is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The PN junction diode IN4007 from the Electrobot manufacturer and digital hot plate are shown in the following *figure 6.6(a)* and *figure 6.6(b)* for reference.

The diode IN4007 is kept on the hot plate, covered with sand, to analyze the failure and fault:

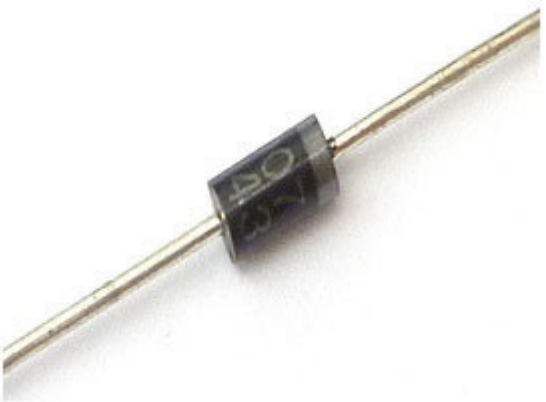




Figure 6.6: *(a) PN junction IN4007 (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components. Choose the 200 samples of the PN junction diode from the Electrobot manufacturer serial num 0720442656985.

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Verify whether all the components are working properly.

Explore the datasheet of the PN junction diode and monitor its stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -40 to 125 degree Celsius in the case of PN junction diode from the Electrobot manufacturer serial num 0720442656985.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 130 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of Bipolar Junction Transistor

For the evaluation of the reliability of a bipolar junction transistor 2N2222 (200 Nos.), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are used.

The **bipolar junction transistor** is an active component which is widely used in toy to satellite, for switching, amplification, and control applications. The reliability of the bipolar junction transistor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The bipolar junction transistor, num 2N2222 of the Electrobot manufacturer, and the digital hot plate are shown in the following *figure 6.7(a)* and *figure 6.7(b)* for reference.

The bipolar junction 2N2222, is placed on the hot plate, covered with sand. The temperature of the hot plate is varied, in order to explore the MTBF and FIT:





Figure 6.7: *(a) Bipolar junction transistor(b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components.

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Choose the 200 samples of the bipolar junction transistor, num 2N2222 of the Electrobot manufacturer.

Verify whether all the components are working properly.

Explore the datasheet of the bipolar junction transistor and monitor its stress parameters. Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -55 to 150 degree Celsius in the case of the bipolar junction transistor, num 2N2222 of the Electrobot manufacturer.

Take the digital hot plate, which displays the temperature, and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 160 degree

Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of thermistor

For the evaluation of the reliability of an NTC thermistor 100k, a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required.

The **thermistor** is an active component which is widely used for circuit protection, time delay, voltage regulation etc. in various industries. The reliability of the thermistor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The 100K NTC thermistor from the Invento manufacturer and the digital hot plate are shown in the following *figure 6.8(a)* and *figure 6.8(b)* for reference.

The NTC thermistor, is placed on the hot plate, covered with sand. The temperature of hot plate is varied, in order to explore the MTBF and FIT.





Figure 6.8: *(a) Thermistor 100K NTC (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components.

The reliability of the components tells the consistency of the performance of the previously said component in an elevated thermal environment.

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Choose the 200 samples of the 100K NTC thermistor from the Invento manufacturer.

Verify whether all the components are working properly.

Explore the datasheet of the thermistor and monitor its stress parameters. Observe the minimum and the maximum range of the previously said component as specified in the datasheet given by the manufacturer, 0 to 100 degree Celsius in the case of 100K NTC thermistor from the Invento manufacturer.

Take the digital hot plate, which displays the temperature, and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 105 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of thyristor

For the evaluation of the reliability of a thyristor BT136, 600V (200 Nos.), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required for experimental setup.

The thyristor is a solid-state semiconductor device which acts as a switch, and is widely used as control elements. The reliability of the thyristor is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The thyristor BT136, 600V, and a digital hot plate are shown in the following *figure 6.9(a)* and *figure 6.9(b)* for reference.

The thyristor BT136, is placed on the hot plate, covered with sand. The temperature of hot plate is varied, in order to explore the MTBF and FIT.



Figure 6.9: *(a) Thyristor BT136 (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components. Choose the 200 samples of the thyristor BT136, BMES manufacturer.

Procedure for experimental testing

The following steps should be followed, with prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Verify whether all the components are working properly.

Explore the datasheet of the thyristor and monitor its stress parameters.

Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -40 to 125 degree Celsius in the case of the thyristor BT136.

Take the digital hot plate, which displays the temperature, and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 130 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of the failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of 555 Timer IC

The datasheet has all the input parameters with a specified range, as well as the performance parameters of the component. But, when it is used in a real-life application, the environmental conditions may vary, which can break down the component and automatically shut down the complete system. In order to operate the electronic device efficiently and fault free, the reliability of that component is calculated in the elevated environmental conditions, so that the user can be warned well before the end of life (EOL) of the component.

Foe the evaluation of the reliability of an NE 555 Timer (200 Nos.), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required for the experimental setup.

The 555 timer is an integrated circuit which acts as a precise timing element and is widely used as a flip-flop element, pulse generator, oscillator, power delay provider etc. The reliability of the NE555 timer is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The NE555 and the digital hot plate are shown in the following *figure 6.10(a)* and *figure 6.10(b)* for reference.

The NE555 timer is placed on the hot plate, and covered with sand. The temperature of the hot plate is varied, in order to explore the MTBF and FIT.



Figure 6.10: *(a) NE555 timer IC (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components.

The reliability of the components tells the consistency of the performance of the previously said component in an elevated thermal environment.

Procedure for experimental testing

The following steps should be followed, with the prescribed precautions to analyse the reliability and assess the remaining useful lifetime of the components:

Choose the 200 samples of the NE555 timer, Electrobot manufacturer.

Verify whether all the components are working properly.

Explore the datasheet of the thyristor and monitor its stress parameters.

Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, 0 to 70 degree Celsius in the case of an NE555 timer.

Take the digital hot plate, which displays the temperature, and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 80 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Evaluation of the reliability of operational amplifier

For the evaluation of the reliability of the Operational amplifier 741 (200 No.s), a datasheet, a digital hot plate, sand, a stop-watch, a multimeter, and a thermometer are required for the experimental setup.

The operational amplifier IC741 is used widely for the amplification purpose. It has been used for the industrial and automation purpose. The reliability of the operational amplifier is measured using the accelerated life testing. In the accelerated life testing, the stress parameters are kept more than the range specified in the datasheet, and the number of failures in a specified time period is observed. The operational amplifier IC741 and the digital hot plate are shown in the following *figure 6.11(a)* and *figure 6.11(b)* for reference.

The **operational amplifier IC741** is placed on the hot plate, and covered with sand. The temperature of the hot plate is varied, in order to explore the MTBF and FIT.

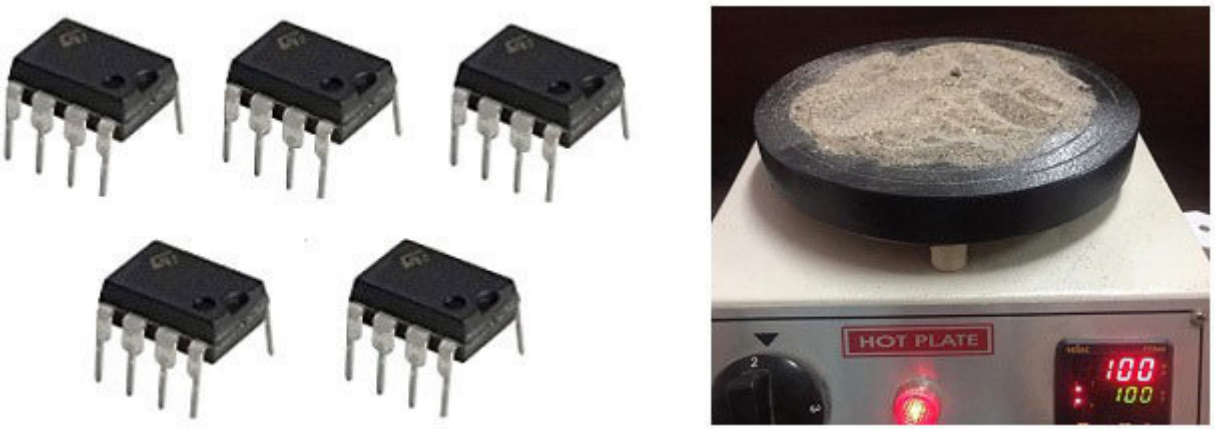


Figure 6.11: *(a) Operational amplifier IC 741 (b) Digital hot plate*

The mean time between failure (MTBF) is calculated using the number of failed components with respect to the time and the total number of components.

Choose the 200 samples of the operational amplifier 741 from the O'Latus manufacturer.

Procedure for experimental testing

The following steps should be followed, with the prescribed precautions to analyse the reliability, and assess the remaining useful lifetime of the components:

Verify whether all the components are working properly.

Explore the datasheet of the thyristor and monitor its stress parameters.

Observe the minimum and maximum range of the previously said component as specified in the datasheet given by the manufacturer, -40 to 85 degree Celsius in the case of the operational amplifier.

Take the digital hot plate, which displays the temperature and note the time using a stop watch.

Cover all the components with sand, so that uniform heating can be provided, and put them on the hot plate.

Start the digital hot plate. Set the initial temperature as 0 degree Celsius and the maximum temperature range as 100 degree Celsius. Augment the temperature in steps of 5-degree increase.

Keep on verifying whether the components are working or not with the help of a multimeter.

Note down the number of failed components and the time duration.

Complete the process, then again note down the total time taken by the experimental process and the total number of failed components and the accurate ones.

Find out the MTBF, MTTF, Failure rate, and the Reliability as per equation (i-iv).

Plot the graph between the MTBF and Reliability.

Cautions to be followed in experiments

While conducting the experiments, the following points are to be taken care of properly:

Do not touch the base of the digital hot plate.

Cover the components with sufficient amount of sand, so that all the components get uniform heating.

Note down the readings properly and discretely.

Before starting the experiment, make sure all the components are accurate and working properly.

Observation tables

The observation tables and the experimental results should be compiled as follows:

Accelerated life testing result

The total number of components=

The total time taken by the complete experimental process=

process= process= process= process=

Table 6.1: *Accelerated Life Testing*

Reliability Calculation

Calculation

Table 6.2: *Reliability calculations*

Plot graph MTBF versus Reliability

The graph between the MTBF and reliability is plotted, which assesses the relation between the reliability values and the mean time between failure.

It is found that there has been many studies that consider the reuse of the components as one of the strategies in achieving the objectives of enhancing the electronic industry. However, the reuse strategy is not easy to implement. One of the major limitations is the lack of information on the remaining useful life of the components. This has prompted many of the researchers to evolve the models for the prediction of the remaining useful life of the components. The failure of the components diminishes the market reputation of the manufacturer, as well as enhances the recurring cost.

Conclusion

This chapter highlights the reliability prediction of the active and passive components, such as the thyristor, thermistor, timer, capacitor, resistor etc., also calculates the MTBF and reliability. The experimental approach, that is, the accelerated life testing is used to analyse the remaining useful lifetime of the active and passive components. The RUL prediction warns the user for the replacement of the faulty components.

In the next chapter, the various artificial intelligence techniques are incorporated for the failure prediction of the components.

Questions

Why is the experimental testing needed for the reliability assessment?

How can you validate the experimental results?

What do you mean by ALT? What is the significance of 'accelerated' in this testing?

What will you do for the uniform heating of the components?

How will you calculate the MTBF and reliability?

Explain the equation of the failure rate for the electronics components.

CHAPTER 7

Intelligent Modelling For Reliability Assessment Using MATLAB

The prediction of reliability and the upcoming failure can be done using the intelligent modelling, which uses the MATLAB tool. The intelligent model emphasises on the use of artificial intelligence for the RUL prediction.

Structure

In this chapter, we will discuss the following topics:

Artificial intelligence techniques for RUL prediction

The steps to use Artificial Neural Networks (ANN)

The steps to use Fuzzy Logics

The steps to use Adaptive Neuro-Fuzzy Inference System (ANFIS)

Objectives

After studying this chapter, the students will be able to learn the MATLAB ANN tool step wise for the reliability prediction using the Artificial Neural Networks, the MATLAB Fuzzy Logic tool step-wise for the reliability prediction using the Fuzzy logic, and the MATLAB ANFIS tool step-wise for the reliability prediction using the Artificial Neural Fuzzy Inference Systems.

Artificial Intelligence: A tool for reliability estimation

An **intelligent model** is the necessity of the hour. Using the intelligent model, the condition of the component can be monitored. The live health prognosis of the component or device can be done, while the component is installed in the project. An artificial intelligence-based model is used to predict and estimate the remaining useful lifetime of the components.

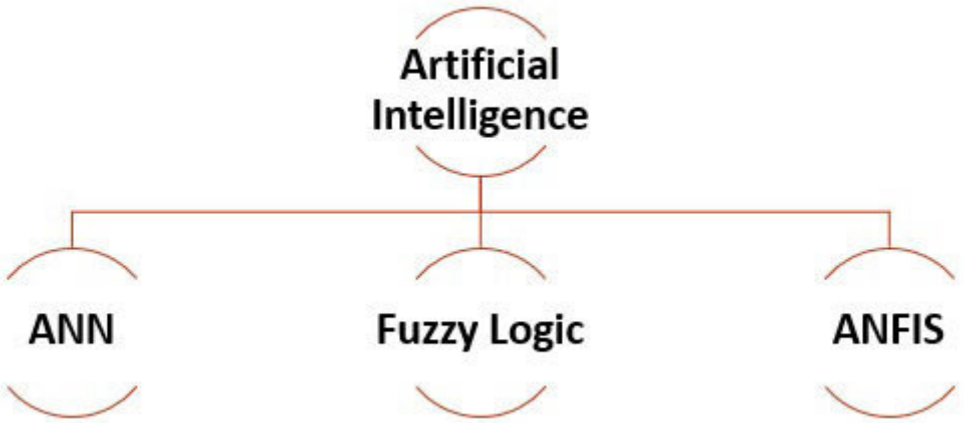


Figure 7.1: *Artificial Intelligence and its techniques*

The preceding figure shows the various types of artificial intelligence techniques that can be employed for the reliability analysis and the RUL prediction. An early warning can notify the user to replace the faulty product or help the user to reuse the component for another project. Thus, the remaining useful life assessment helps to minimise the problem of e-waste.

Reliability Assessment Using Artificial Neural Networks (ANN)

Let us take a case of an electrolytic capacitor, where there are five input parameters, and a single output parameter. An expert system is designed using the following steps:

Right click on the workspace---new----name it.

Three files will be created in the workspace, one for the input, one for the sample (only one column of input), and one for the output.

When you click on the name, a workspace will be opened.

Paste the excel data (transpose form) into the worksheet.

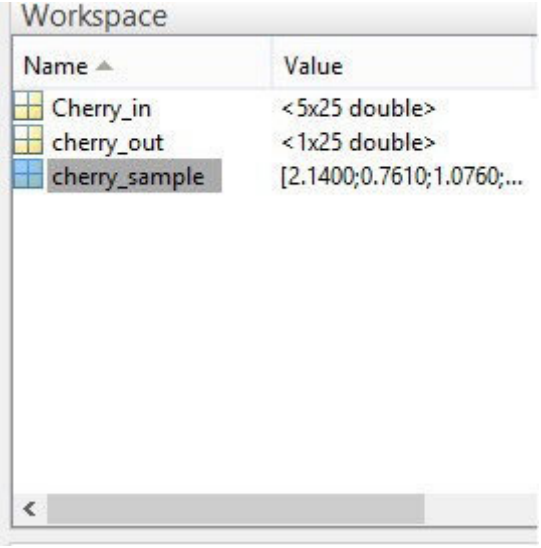


Figure 7.2: *Workspace in MATLAB*

Function--->nntool:

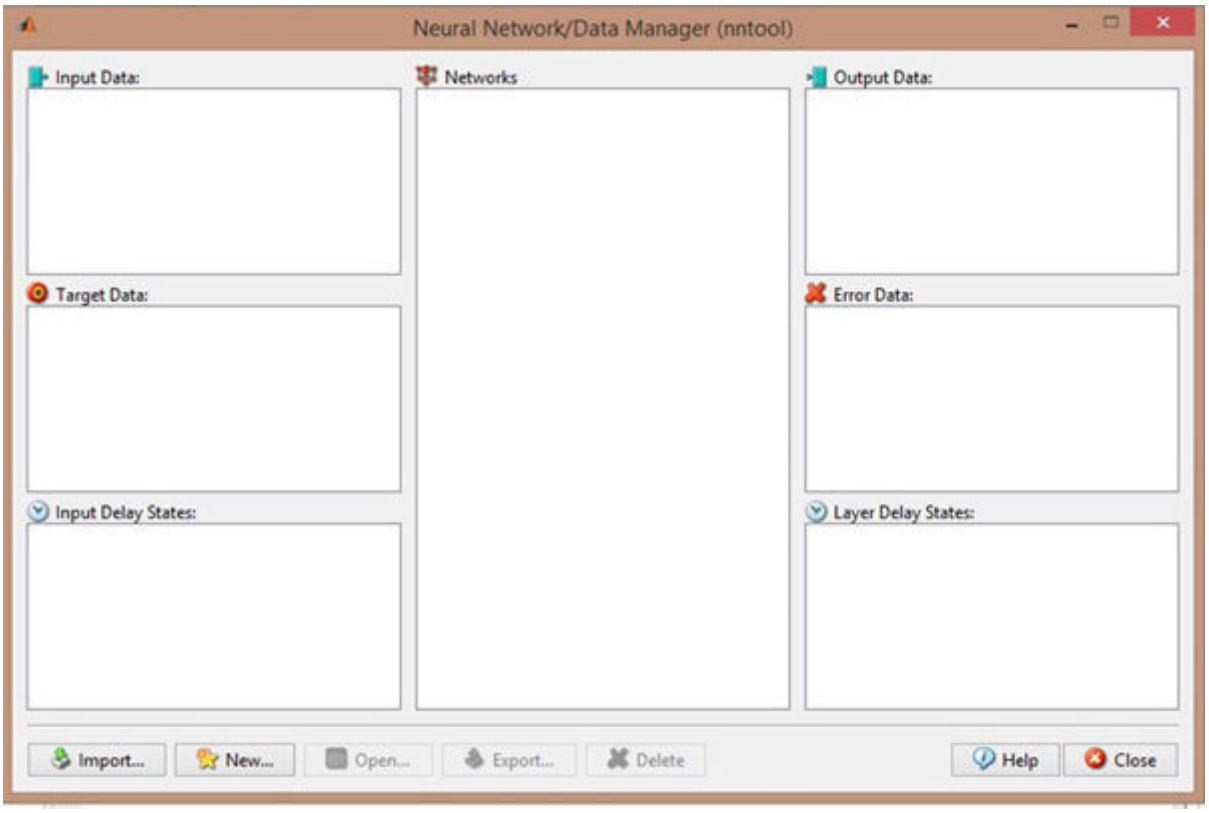


Figure 7.3: *nntool window in MATLAB*

Click on the input data—import:

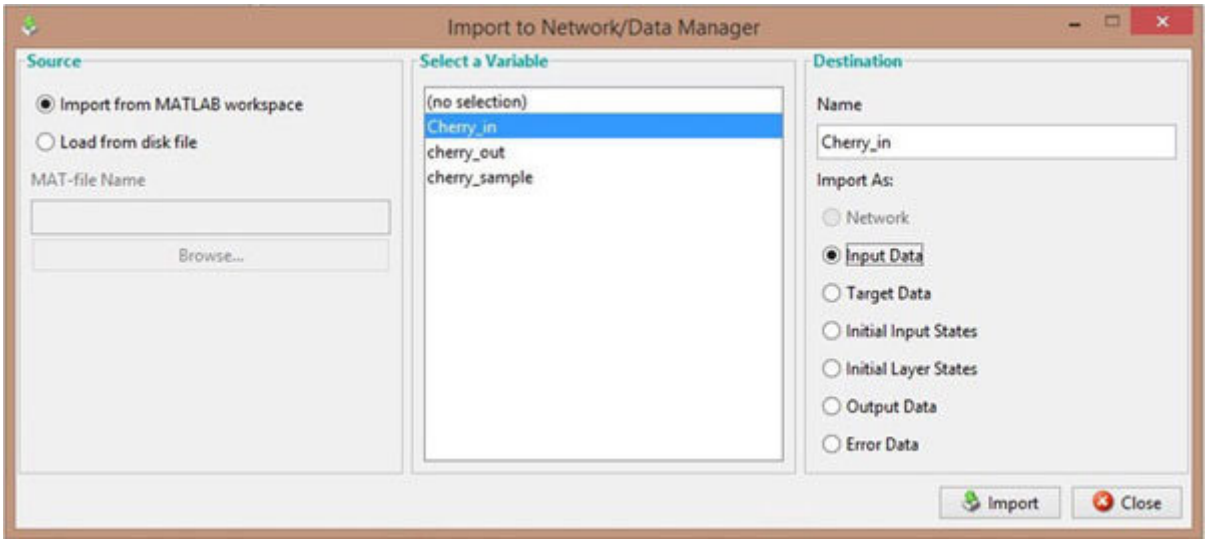


Figure 7.4: *nntool import window in MATLAB*

Click on the input---import data (for the sample):

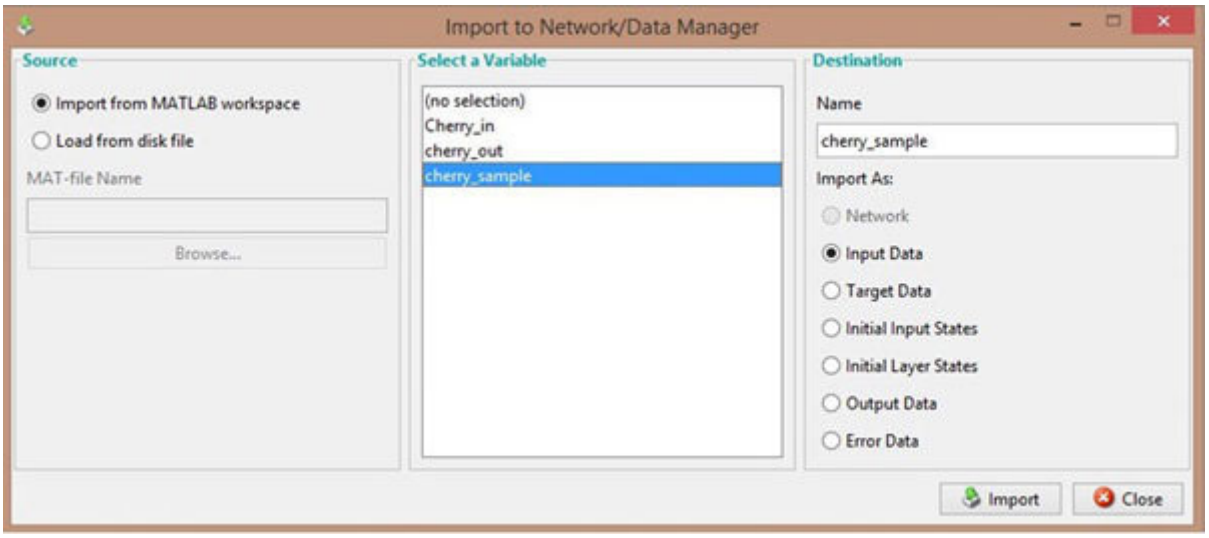


Figure 7.5: *NNtool import input data window in MATLAB*

Click on target—import data (output):

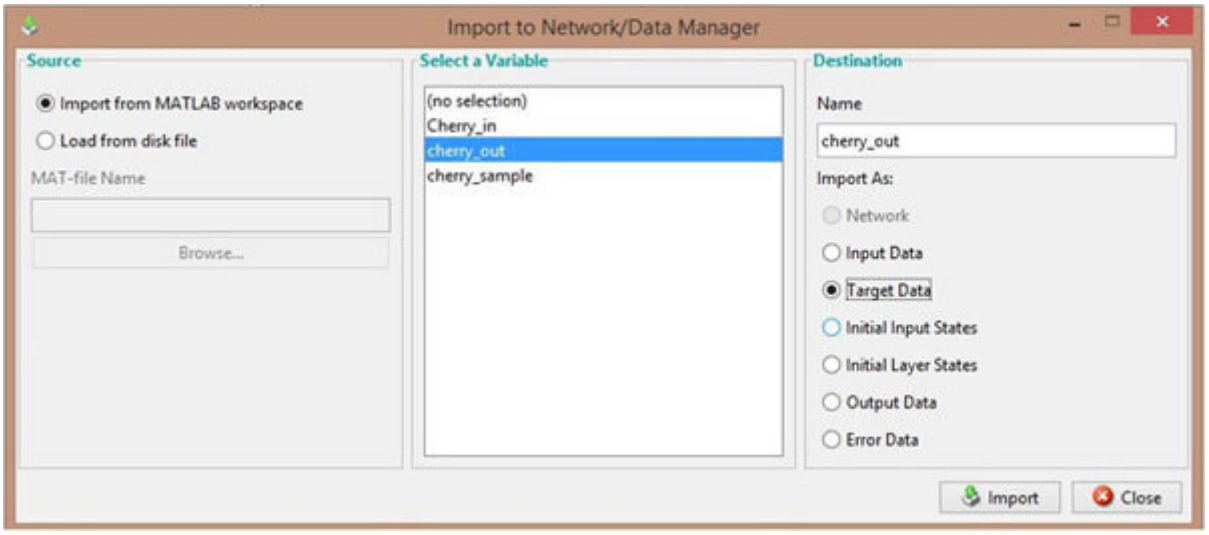


Figure 7.6: *nntool import outout data window in MATLAB*

Click on the networks—new:

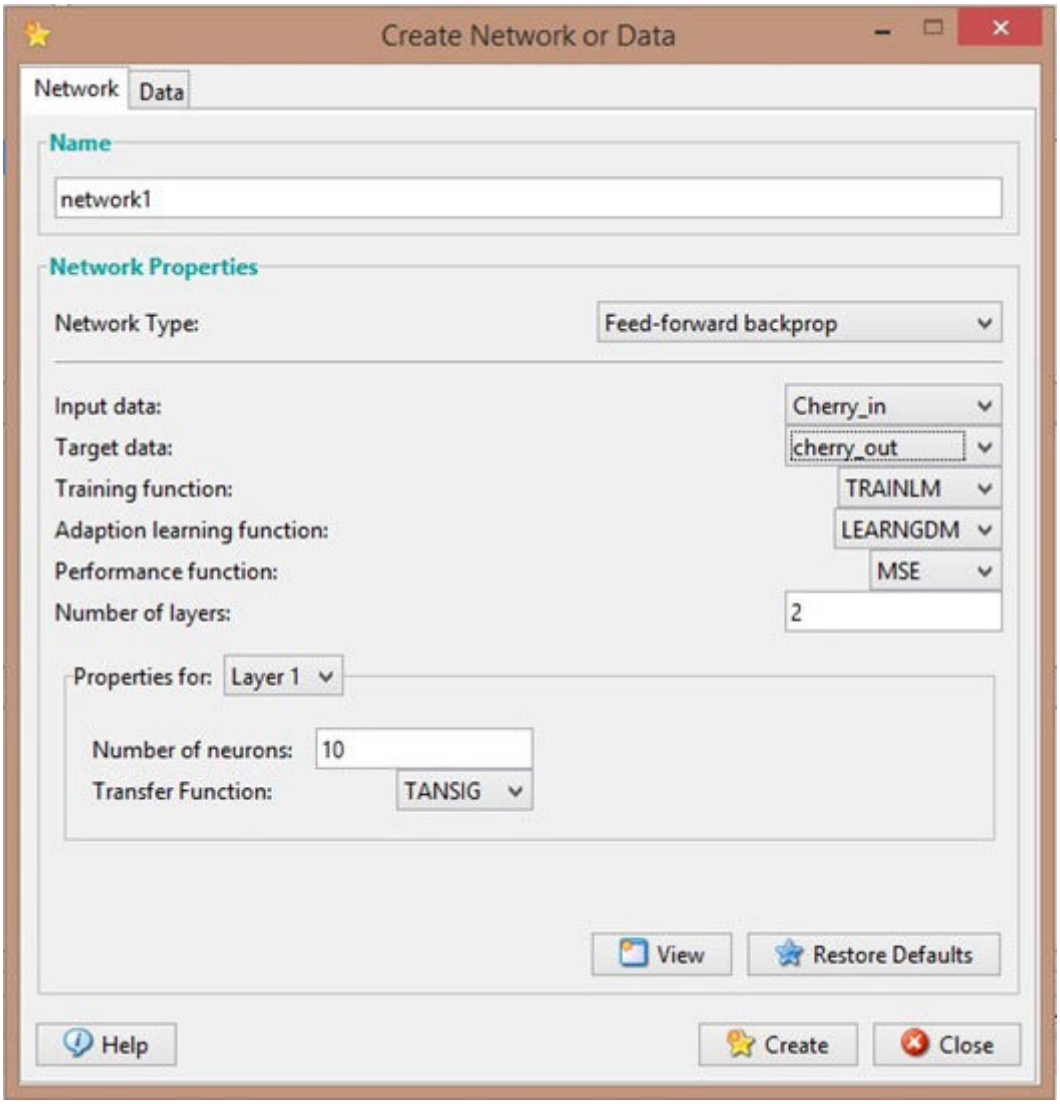


Figure 7.7: *nntool network window in MATLAB*

Click on the network1—open:

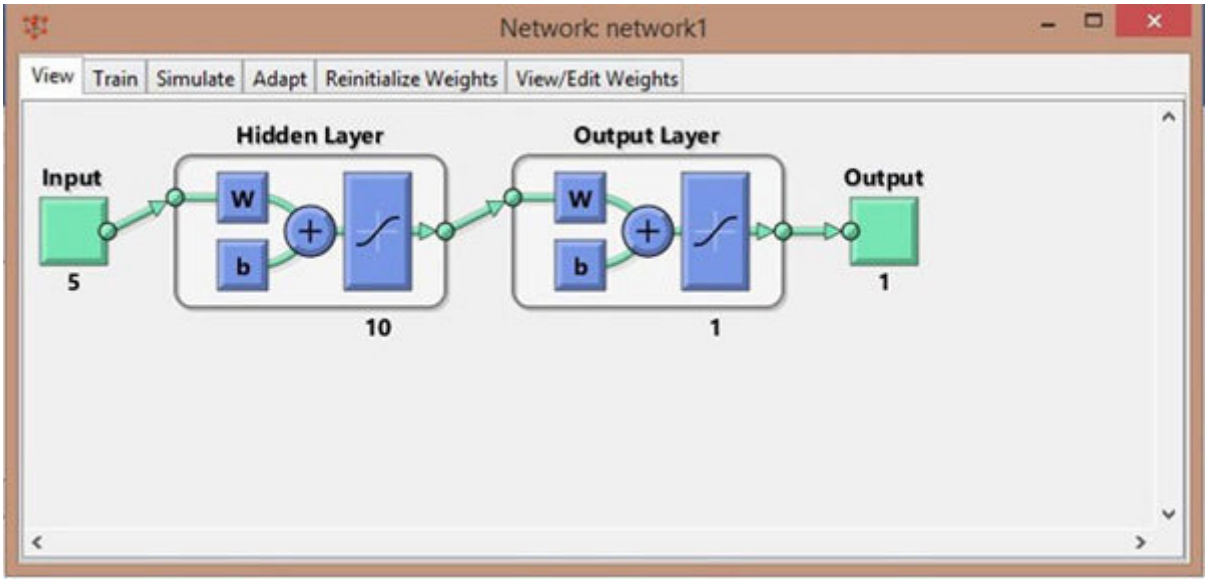


Figure 7.8: *nntool network layers window in MATLAB*

Train—

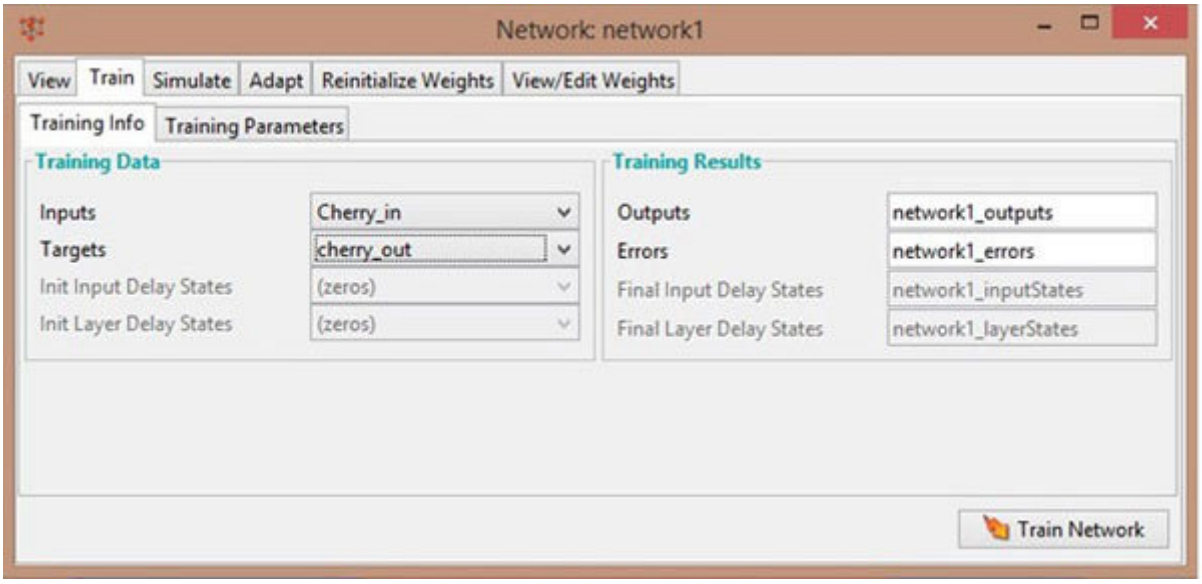


Figure 7.9: *nntool network train window in MATLAB*

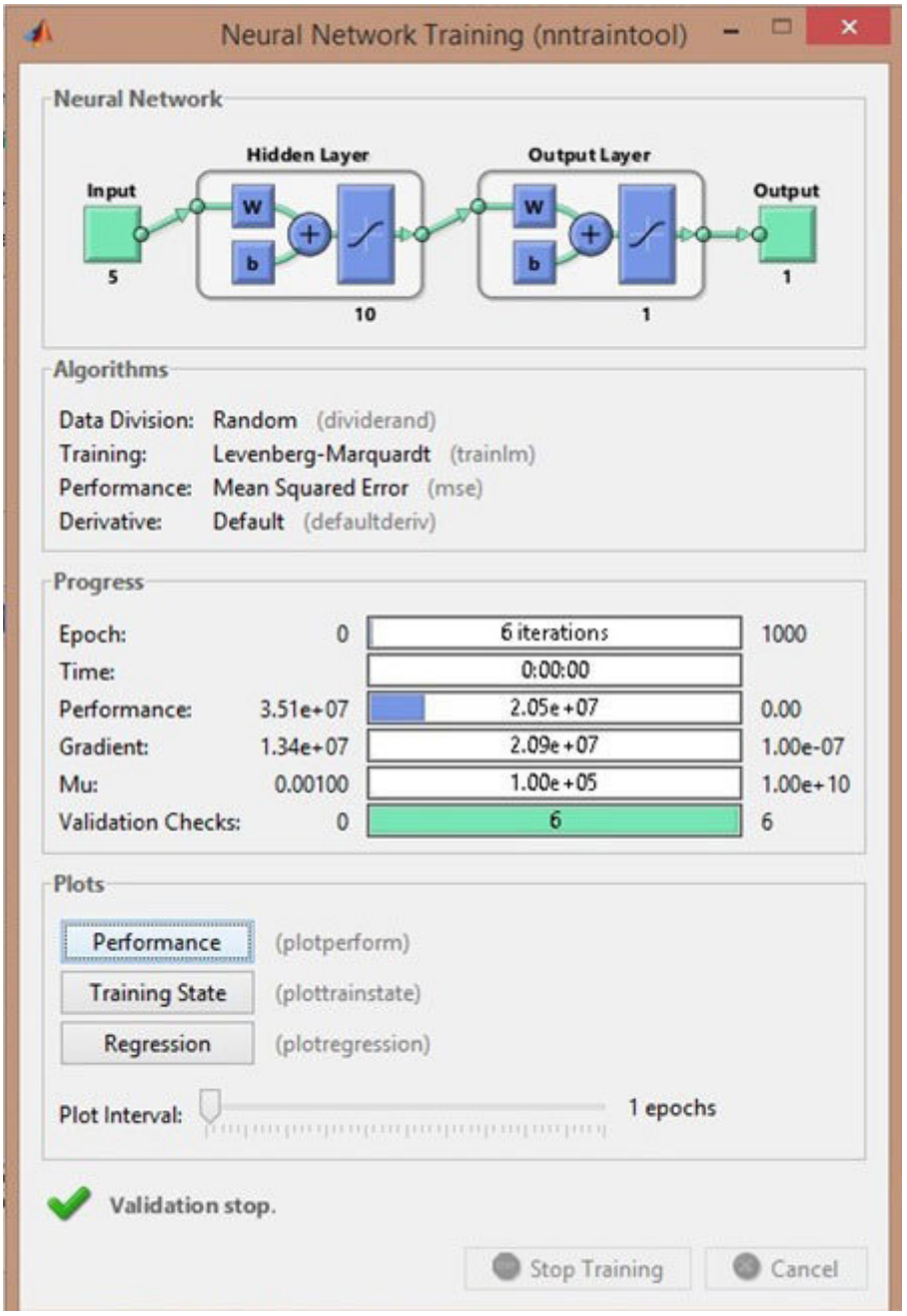


Figure 7.10: *nntool network train output window in MATLAB*

Simulate:

Input—sample

Change name of output

Then simulate

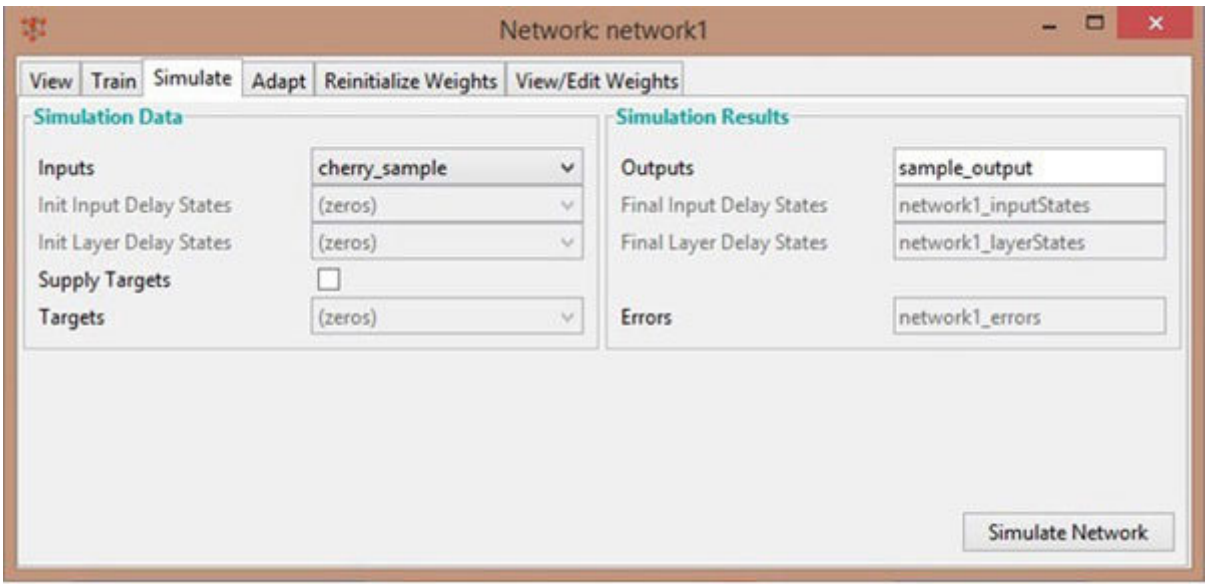


Figure 7.11: *nntool network simulate window in MATLAB*

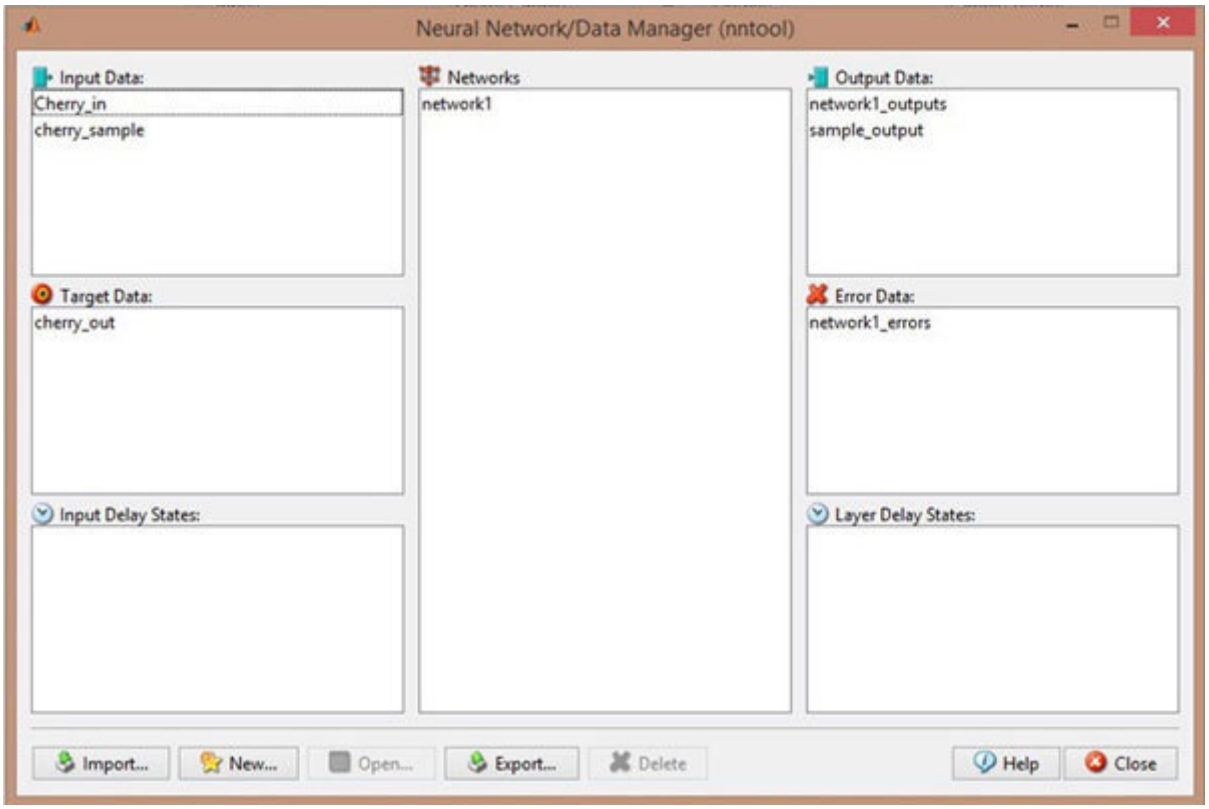


Figure 7.12: *nntool network window with output files in MATLAB*

Click on network1_output:

Export—select all.

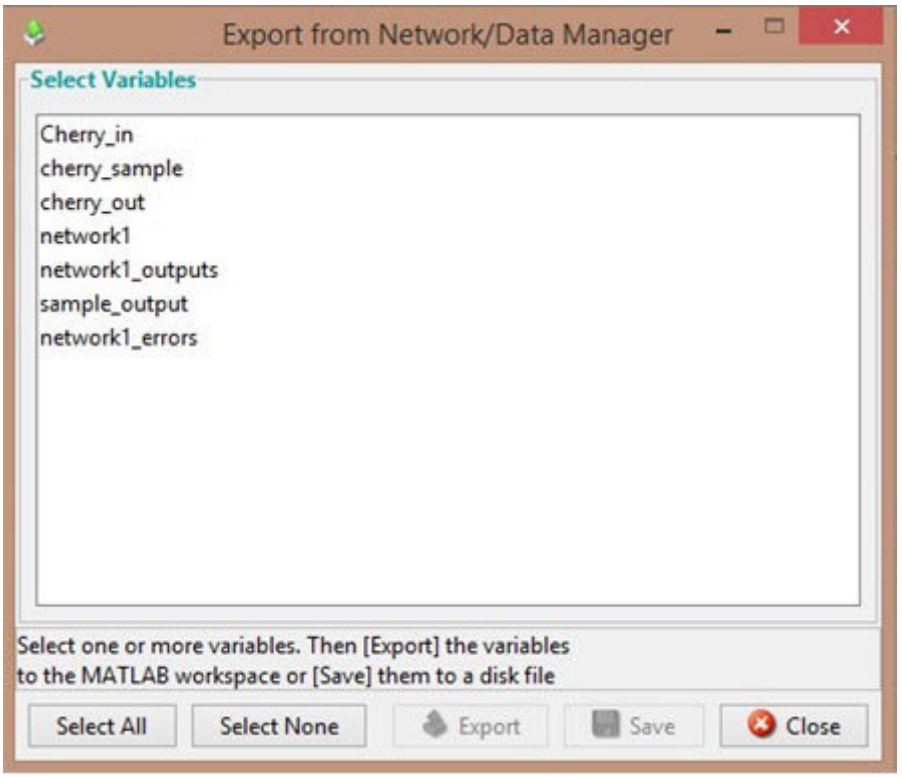


Figure 7.13: *nntool network export selection window in MATLAB*

Export and it will be in the workspace:

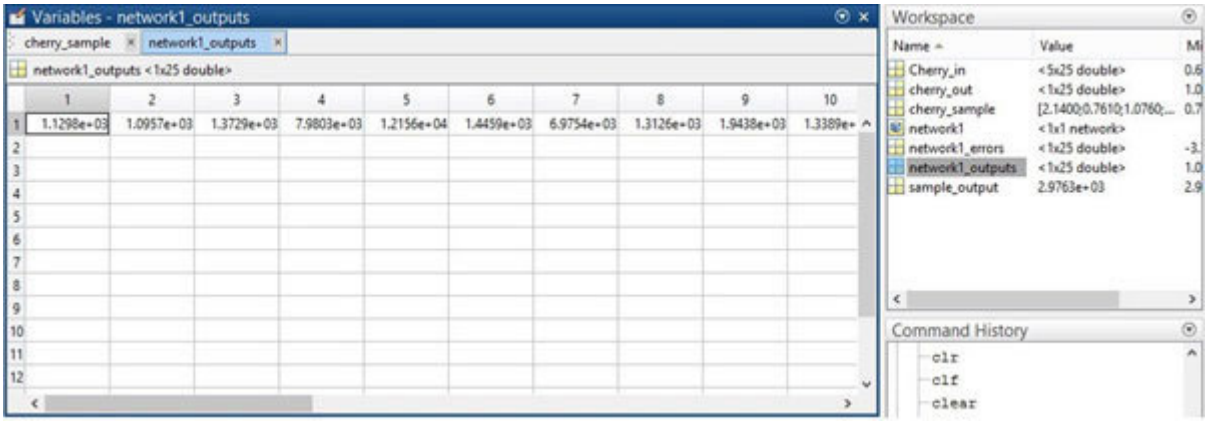


Figure 7.14: *nntool workspace window with output files in MATLAB*

Reliability Assessment Using Fuzzy Logic (FL)

Let us take a case of an electrolytic capacitor, where there are five input parameters, and a single output parameter. An expert system is designed using the fuzzy logic as per the following steps:

Open the MATLAB toolbox:

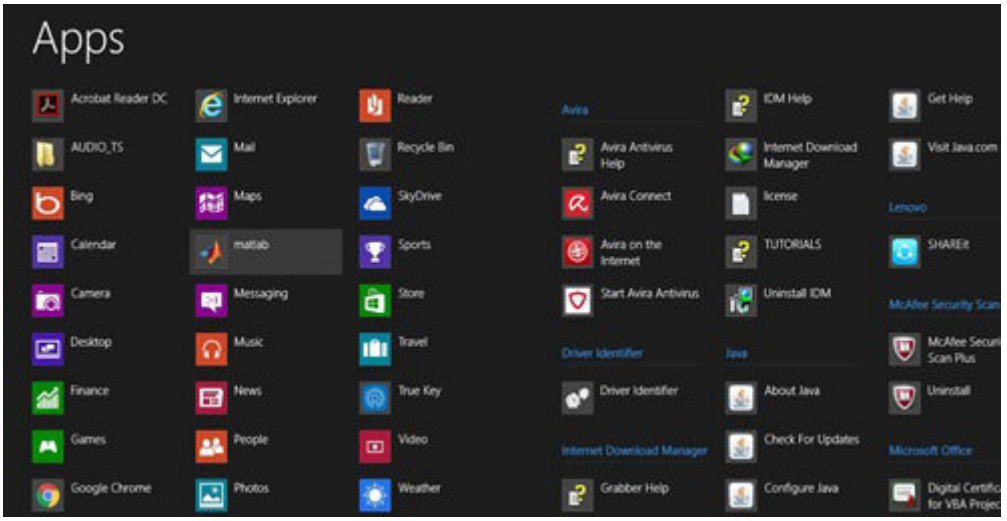


Figure 7.15: *Application window of PC to start MATLAB*

Open fuzzy using the "Fuzzy" command in the command window of the MATLAB toolbox:



Figure 7.16: *Function windows of MATLAB*

The Fuzzy editor window will get opened:

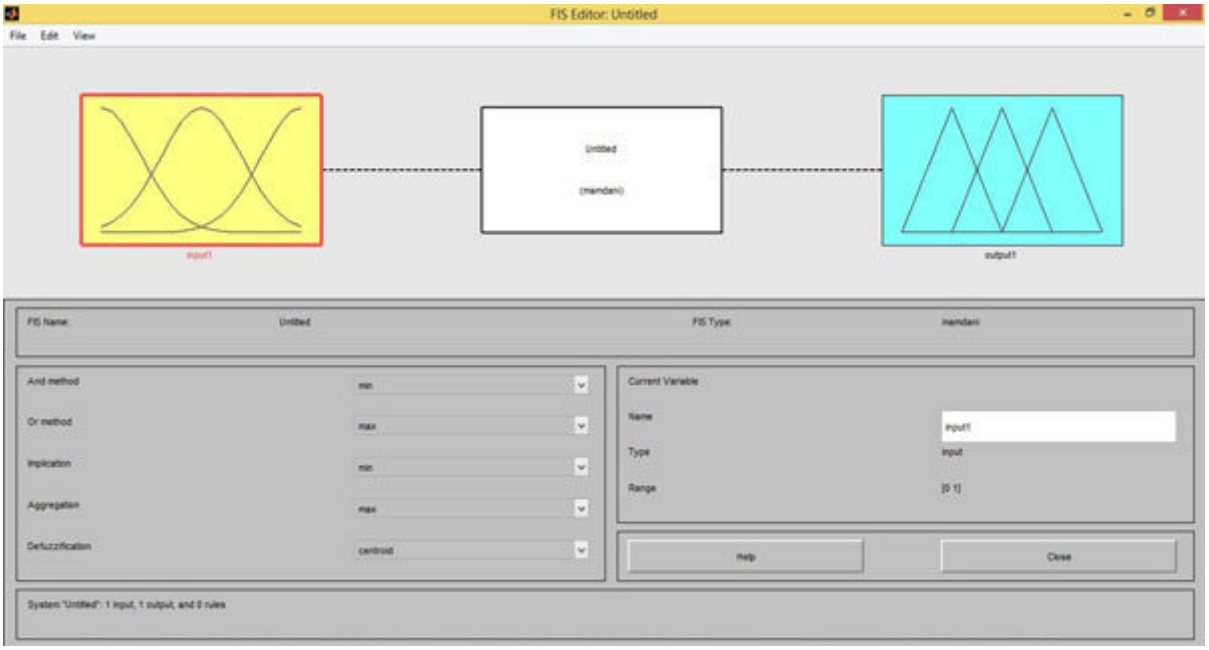


Figure 7.17: *Fuzzy edit window in MATLAB*

Now, add the number of inputs as per the number of input variables using the "Edit" menu. In the edit menu, go to the "Add variable" and then select the "input or output" according to the number of inputs and output:

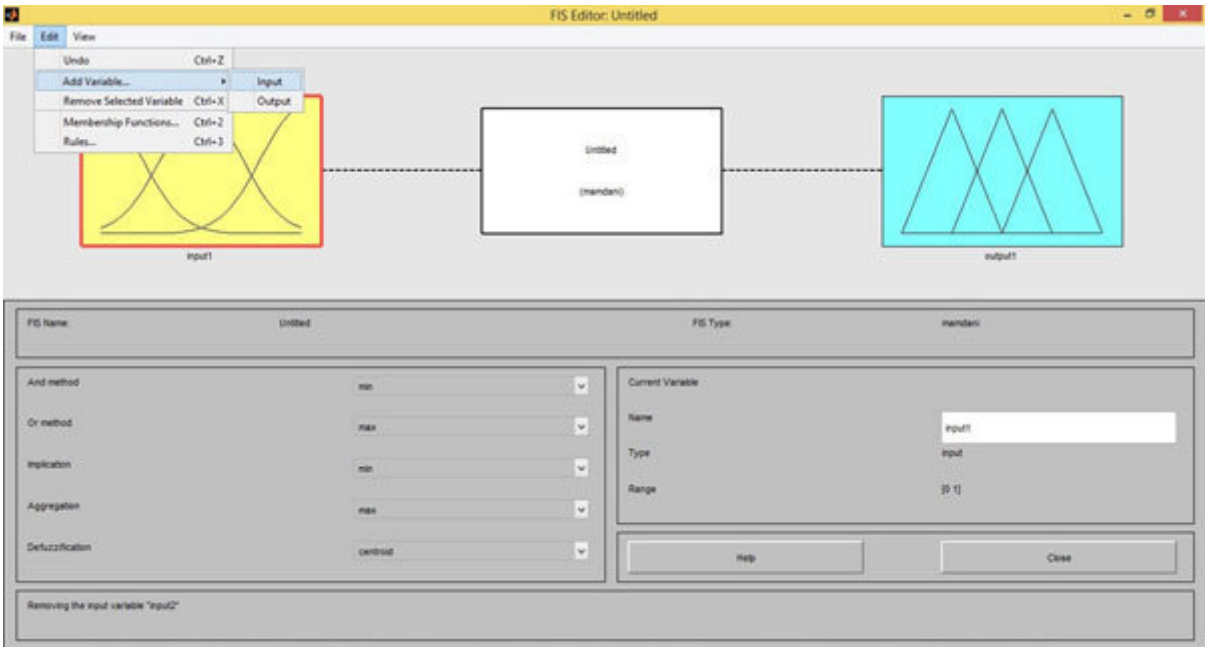


Figure 7.18: *Adding input functions using fuzzy edit window in MATLAB*

The selected number of inputs will be available on the FIS editor window. Rename the inputs by changing the name in the dialog box beyond the "Name" that is shown in the following Fuzzy structure:

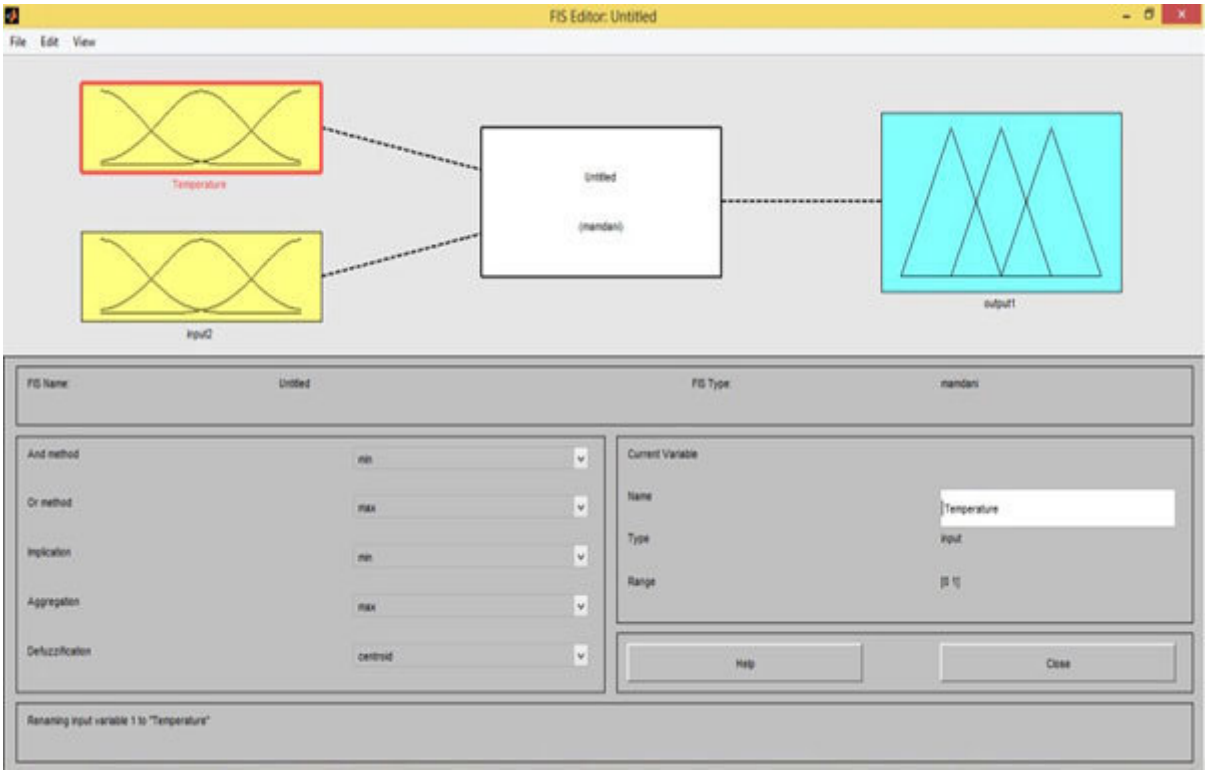


Figure 7.19: *Changing input functions names using the fuzzy edit window in MATLAB.*

In the same way, name of another input and output can be changed.

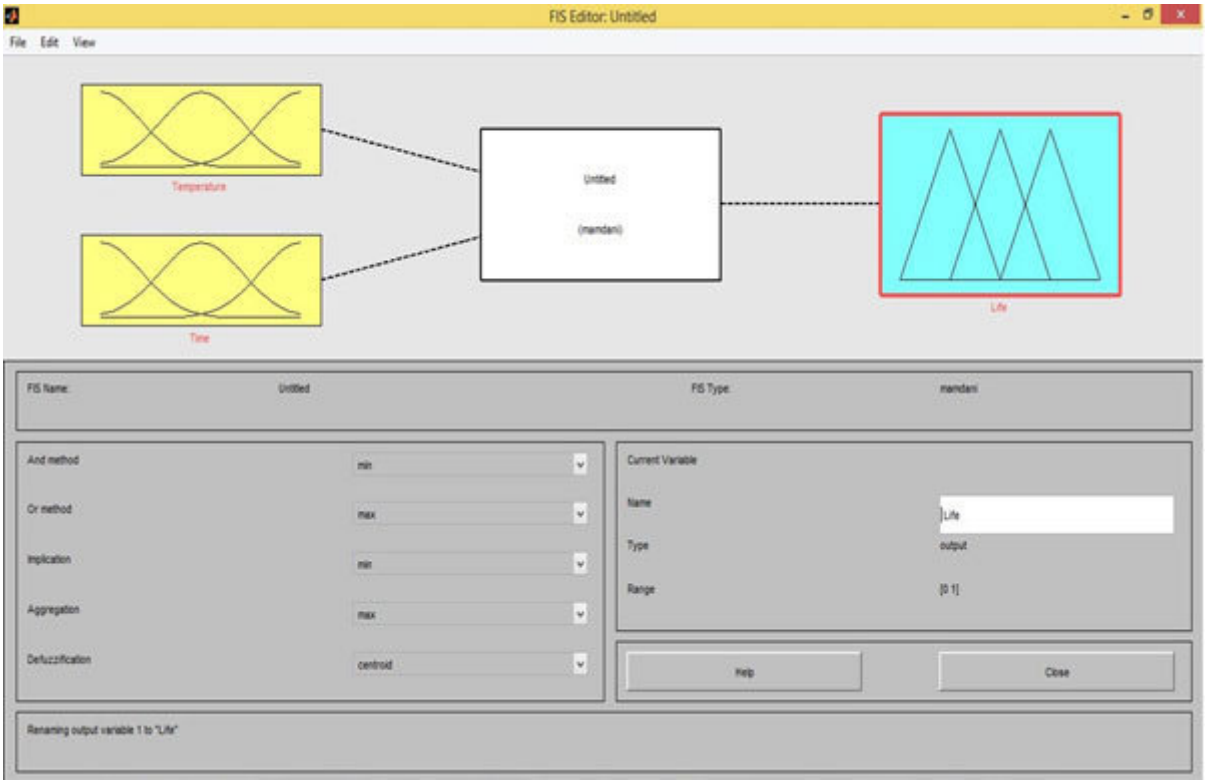


Figure 7.20: *Fuzzy edit window showing output parameter in MATLAB*

In the next step, the input and the output data are loaded in the input and output variables in the form of linguistic variables by selecting the particular variable. The variable will be selected by double clicking that particular variable and the membership function editor window will get opened:

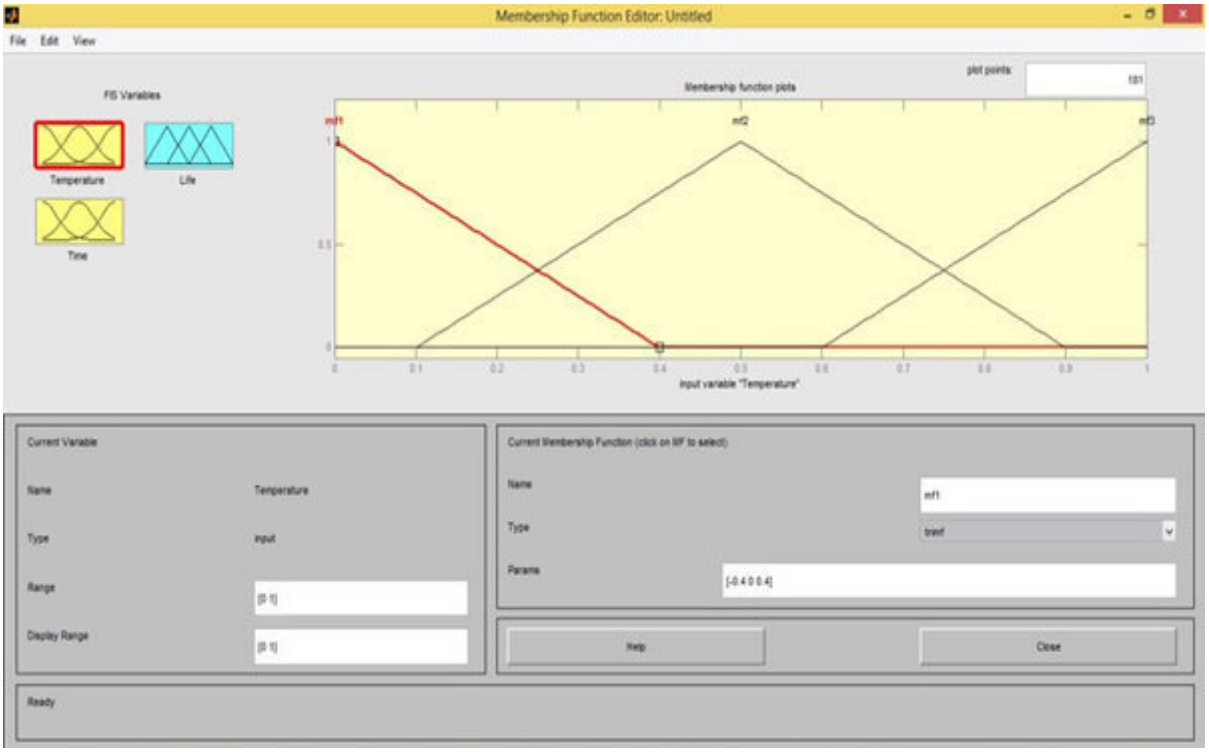


Figure 7.21: *Membership functions edit window*

The membership function can be of any type, such as triangular, Gaussian, or trap etc., and one of all these types will be selected according to the range of loaded data. The name of the membership functions can also be changed using the "Add MFs" from the edit menu.

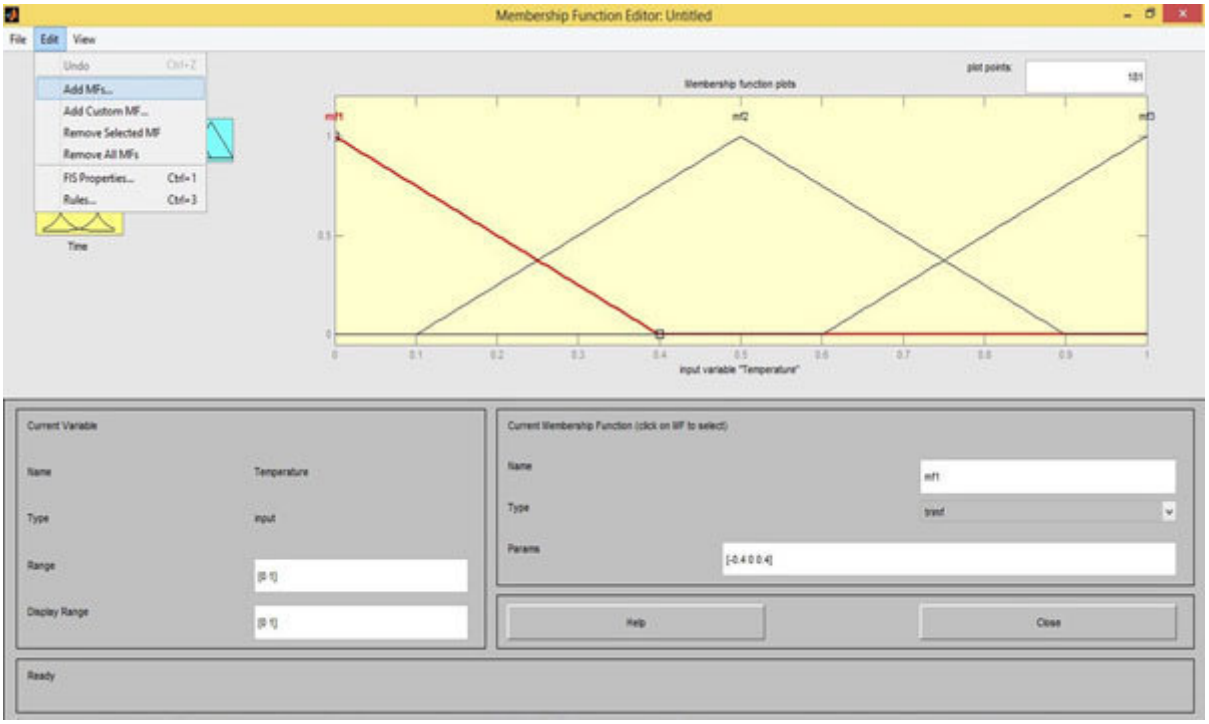


Figure 7.22: *Adding membership functions using membership functions' edit window in MATLAB*

The name and range of the membership functions are changed by selecting each of the membership function. The range of the input variables is also changed by editing the range in the edit box named as "Range", as shown in the following figure:

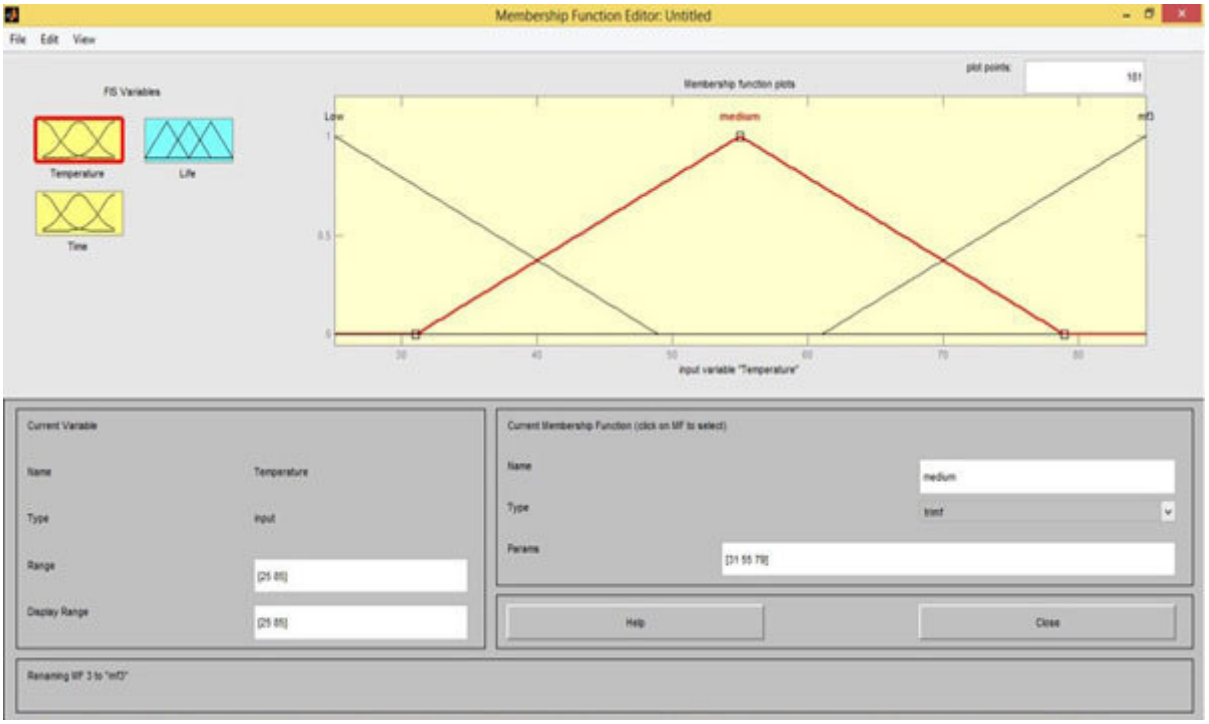


Figure 7.23: *Modifying membership functions using the membership functions' edit window in MATLAB*

In the same way, the range and name of the membership functions of all the inputs and output will be changed as per the range of data.

After editing all the input and output variables, the rules are defined using the edit menu, and then the rules:

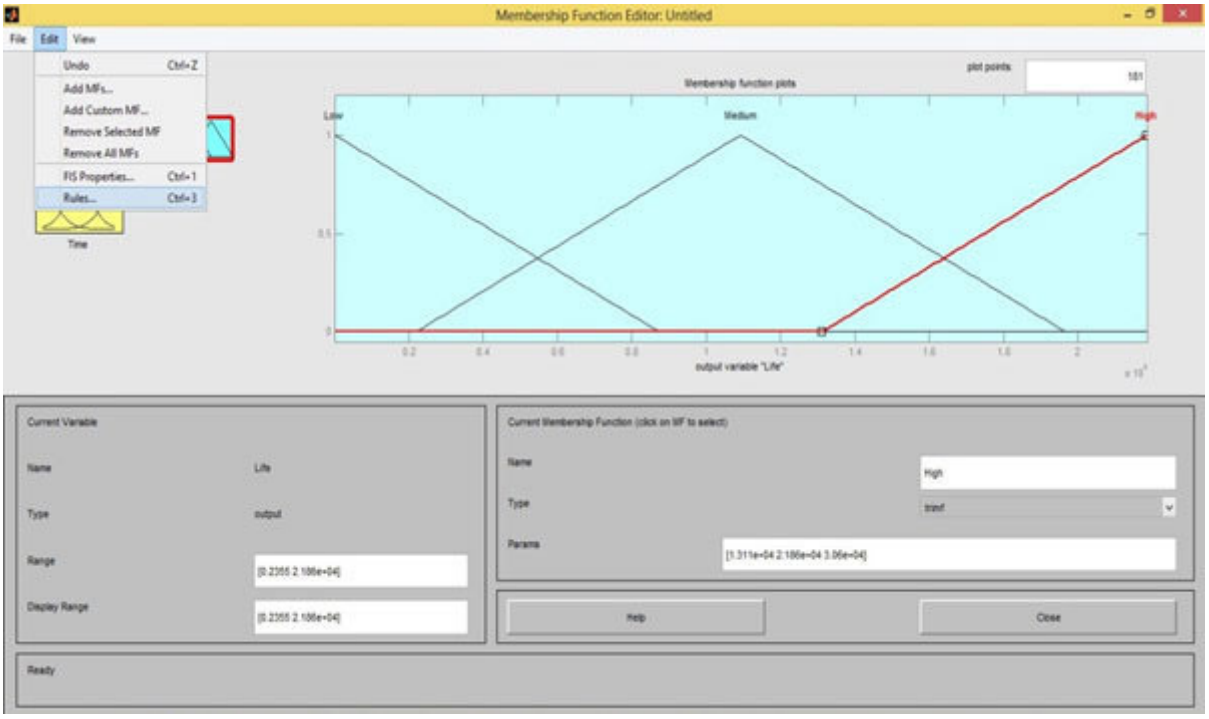


Figure 7.24: *Rules window in MATLAB*

A rule editor window gets opened after selecting the rules by pressing on the right click:

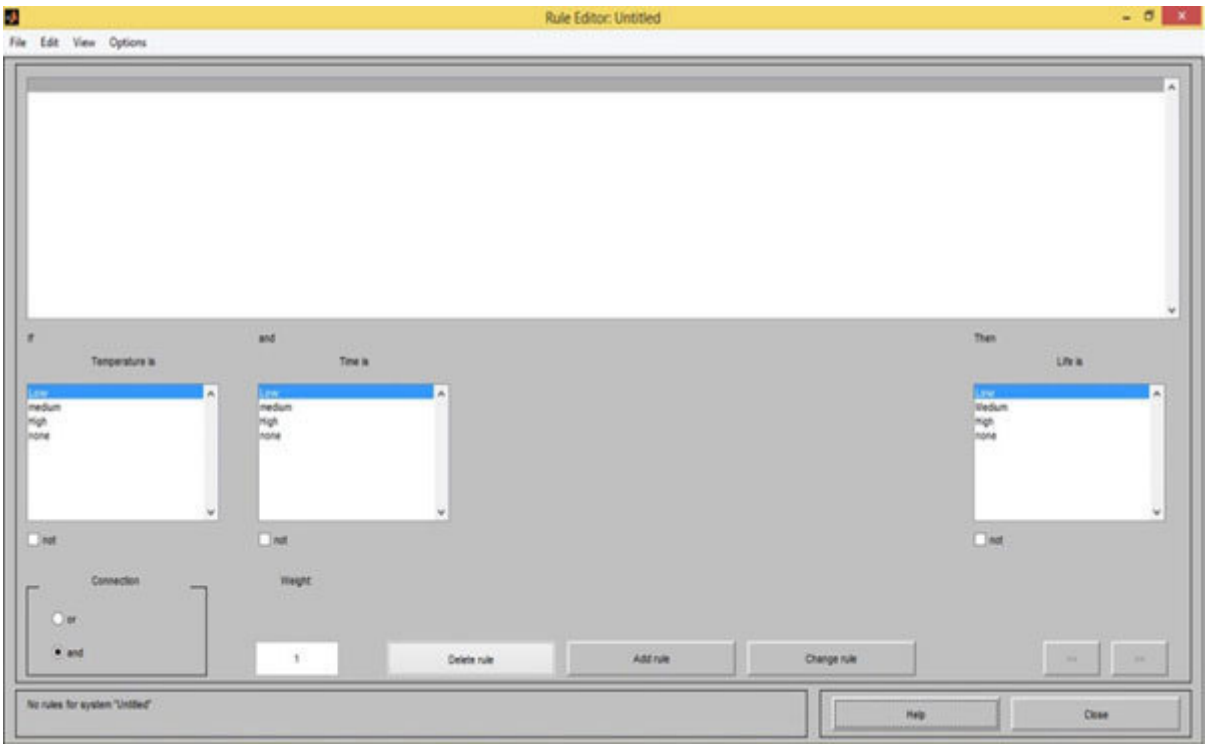


Figure 7.25: *Define rules using rules edit window in MATLAB*

The rules are defined for each combination of inputs with the output, such as when both the inputs (time and temperature) are at a lower range, the output (life) will be high.

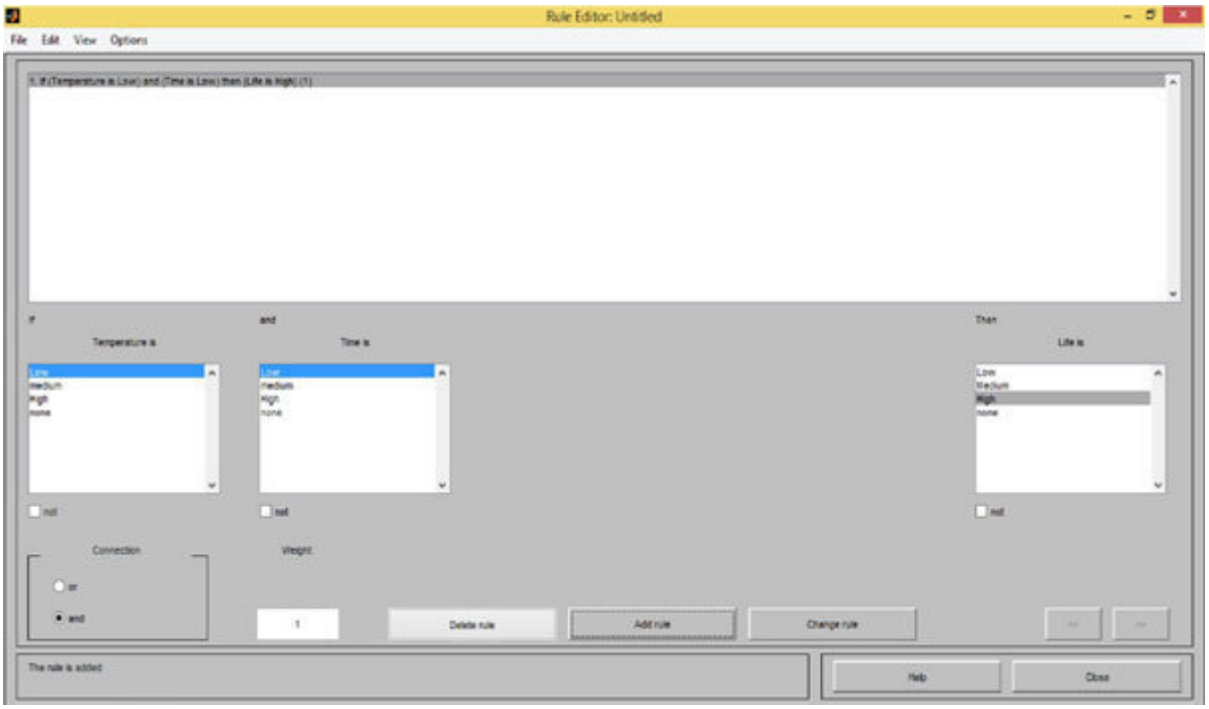


Figure 7.26: *Adding another rule using rule edit window in MATLAB*

Similarly, the rules will be defined for every combination of the inputs and output, such as if the input has 3 membership functions – low, medium, and high – and if the output also has 3 membership functions, the 3*3 = 9 rules will be formed.

Once all the rules are defined, the output is verified by viewing the rule viewer using the view menu and then by selecting

"Rules":

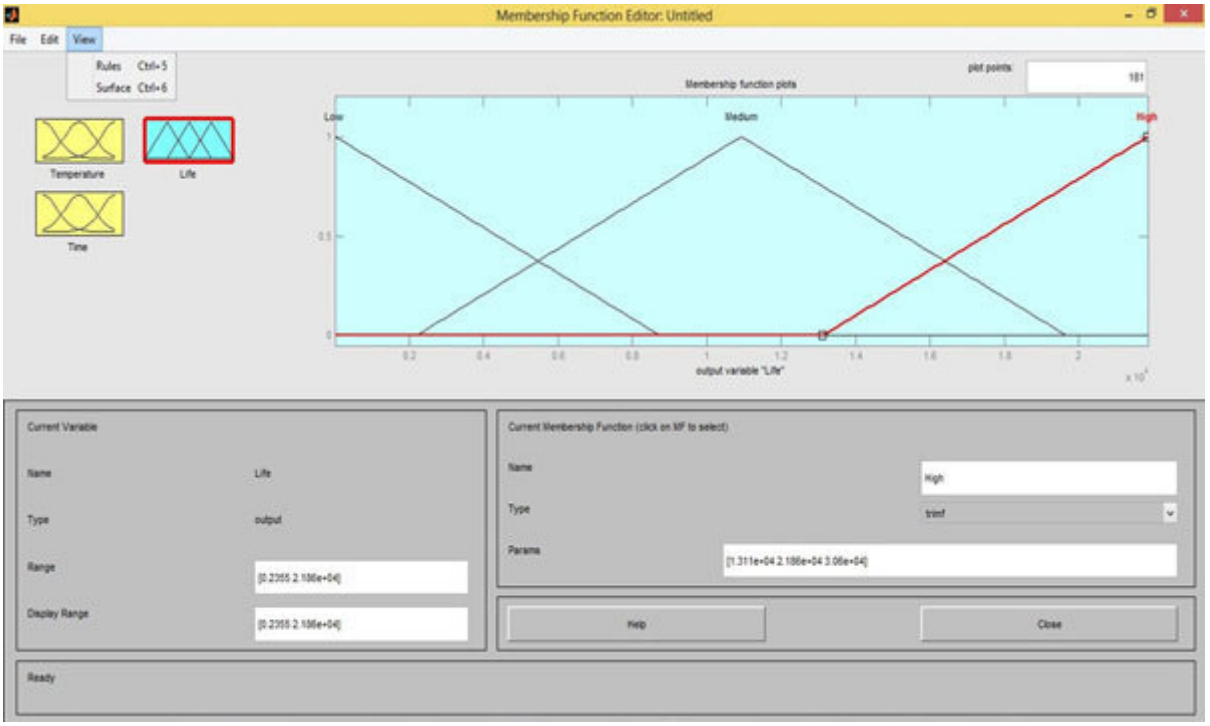


Figure 7.27: *View rule using view window in MATLAB*

The rule viewer window gets opened and from this window, the output is obtained by giving the input data ranges in the input dialog box:

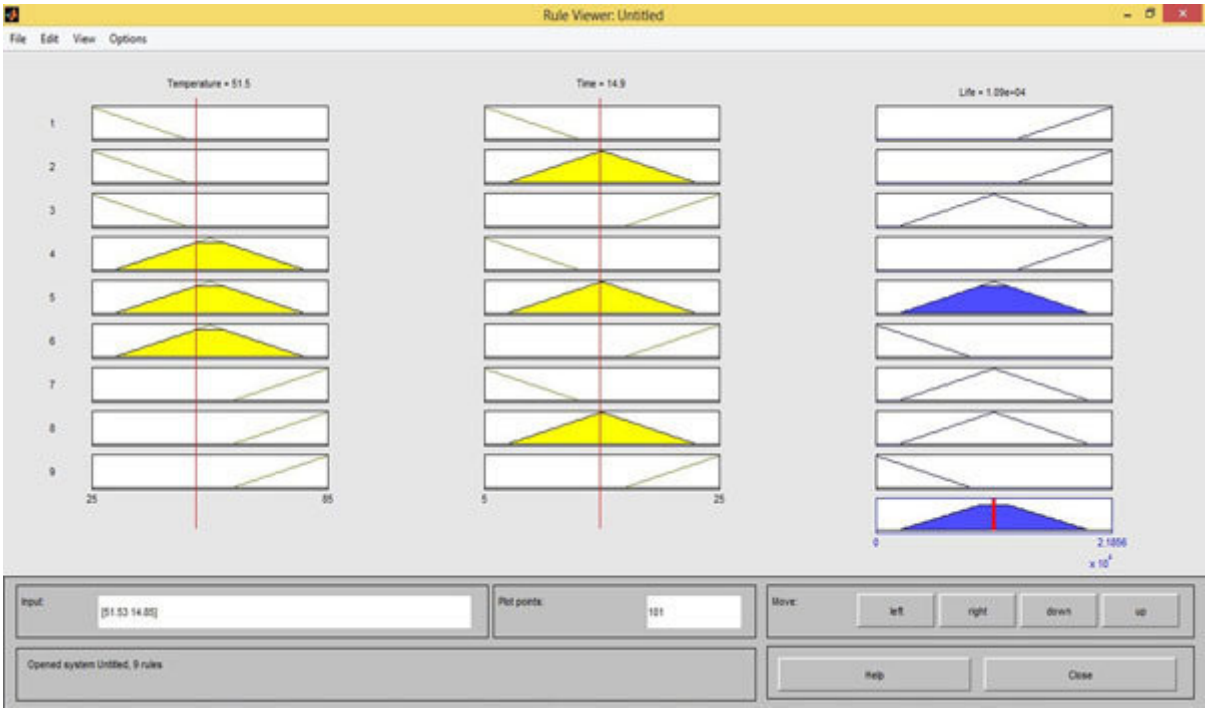


Figure 7.28: *Rule viewer window in MATLAB*

Reliability Assessment Using Adaptive Neuro Fuzzy Inference System (ANFIS)

Let us take a case of an electrolytic capacitor, where there are five input parameters, and a single output parameter. An expert system is designed using ANFIS as per the following steps:

Open MATLAB and ANFIS window by command anfisedit.

On the right side, the workspace is there. Right click---new----name:

Double click – open excel

Copy paste own data



Figure 7.29: *Function window in MATLAB*

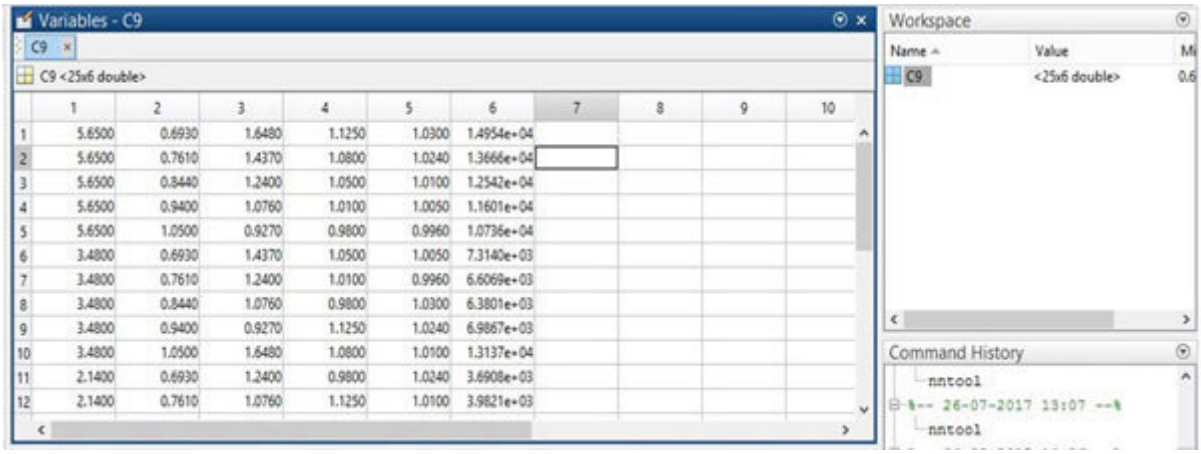


Figure 7.30: *Edit input window in the workspace (MATLAB)*

Close it.

After writing >>anfisedit

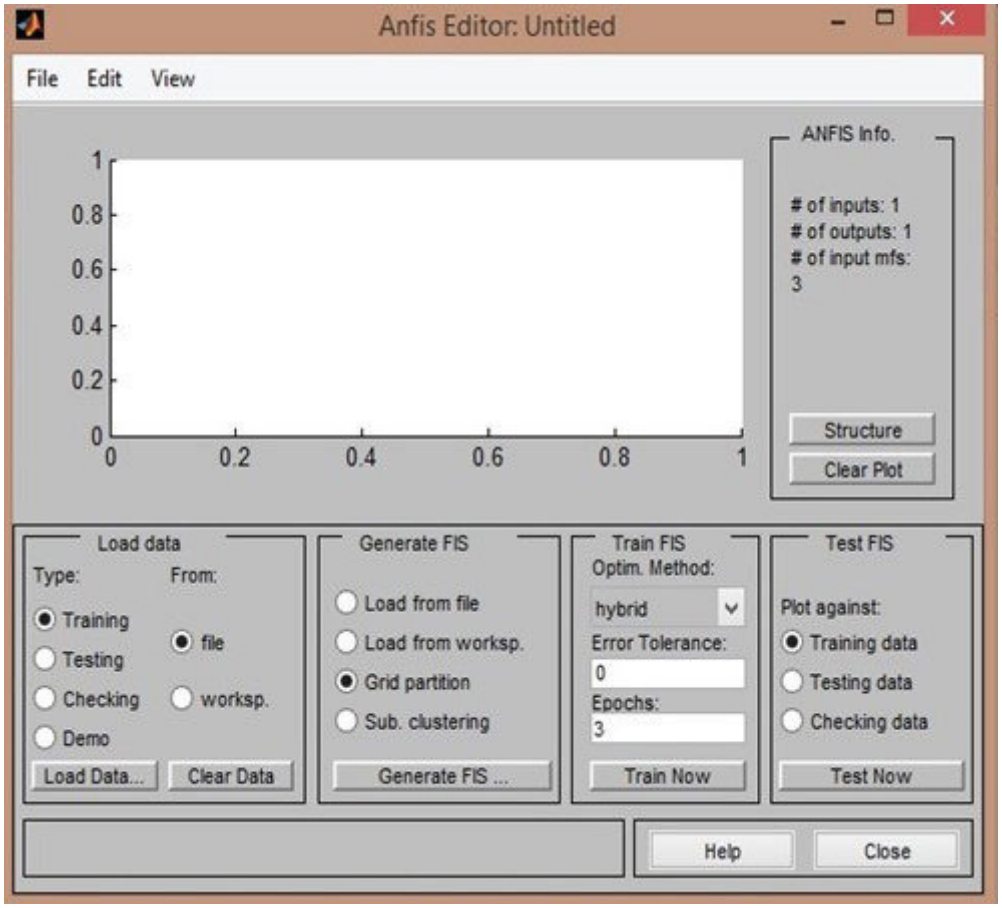


Figure 7.31: *ANFIS edit window in MATLAB*

LOAD data—training—wrksp—click on load data:

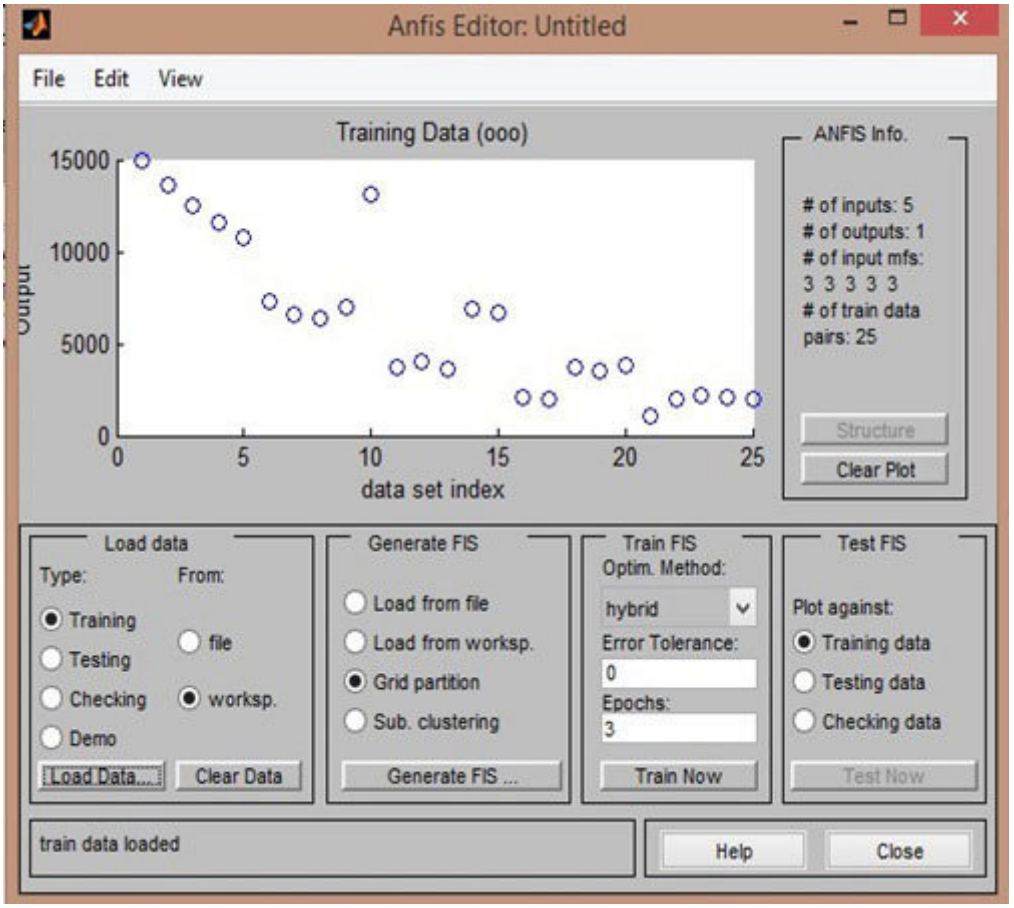


Figure 7.32: *Load training data in ANFIS editor window (MATLAB)*

Generate FIS:

Select membership function—gaussian

MF type—linear

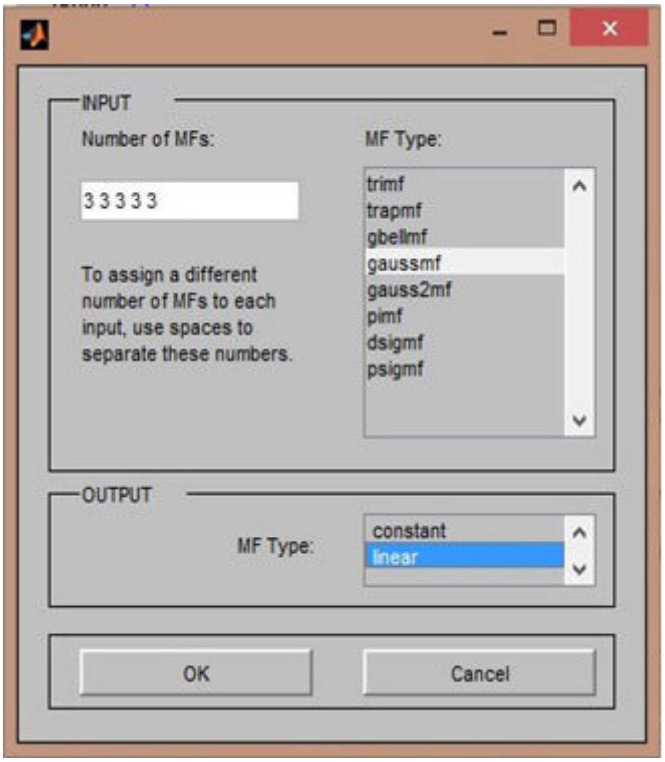


Figure 7.33: *Select MF type in ANFIS editor window (MATLAB)*

Train now—epochs-50:

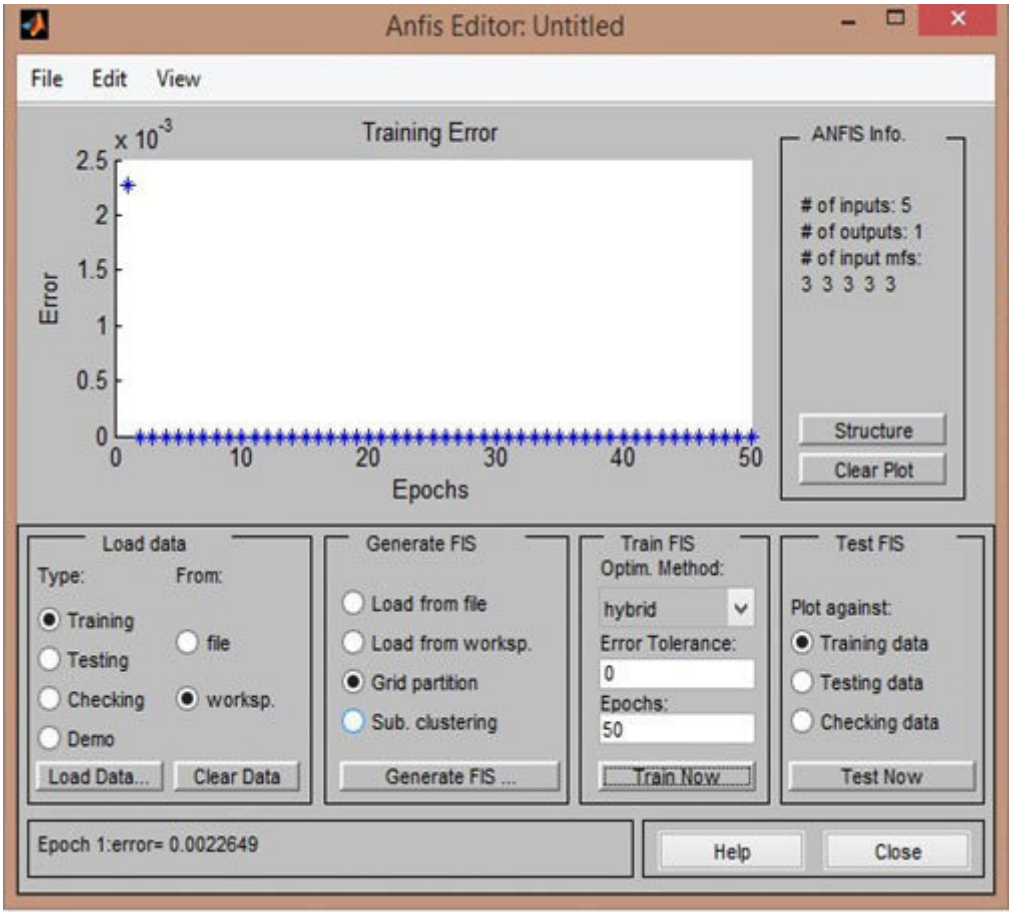


Figure 7.34: *Select epochs in ANFIS editor window (MATLAB)*

Test FIS:

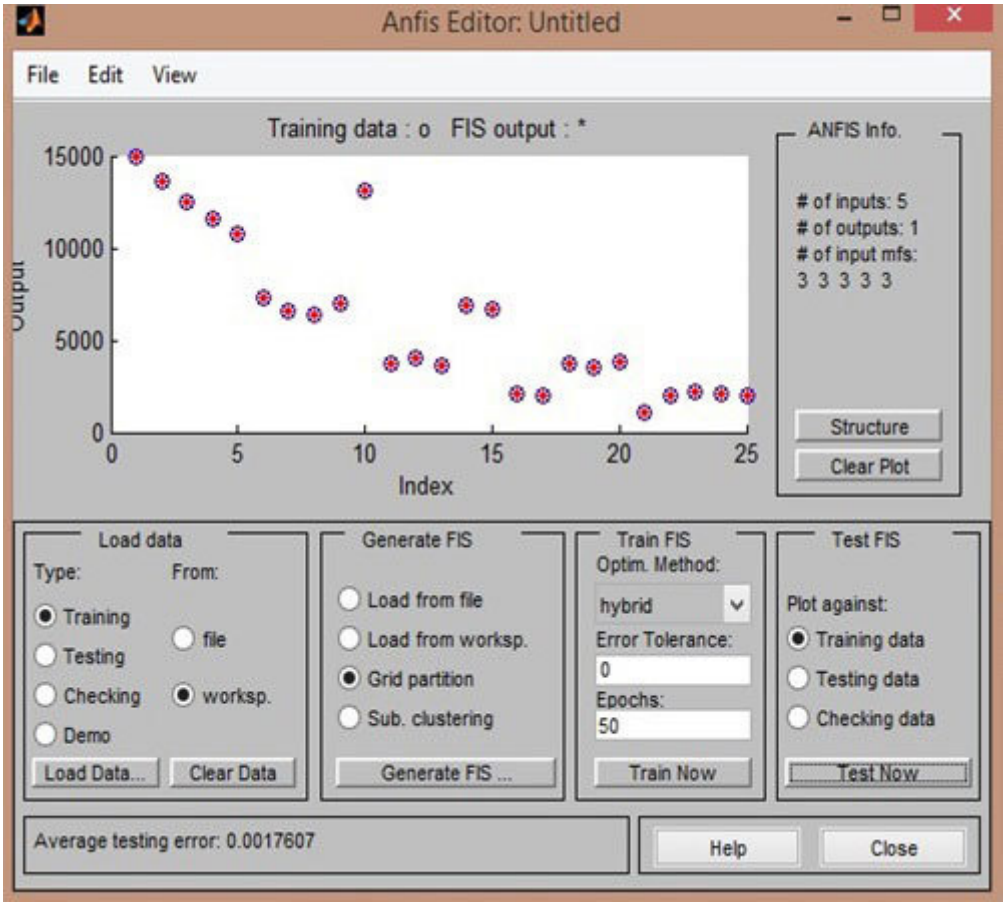


Figure 7.35: *Training window in the ANFIS editor window (MATLAB)*

Click on Structure:

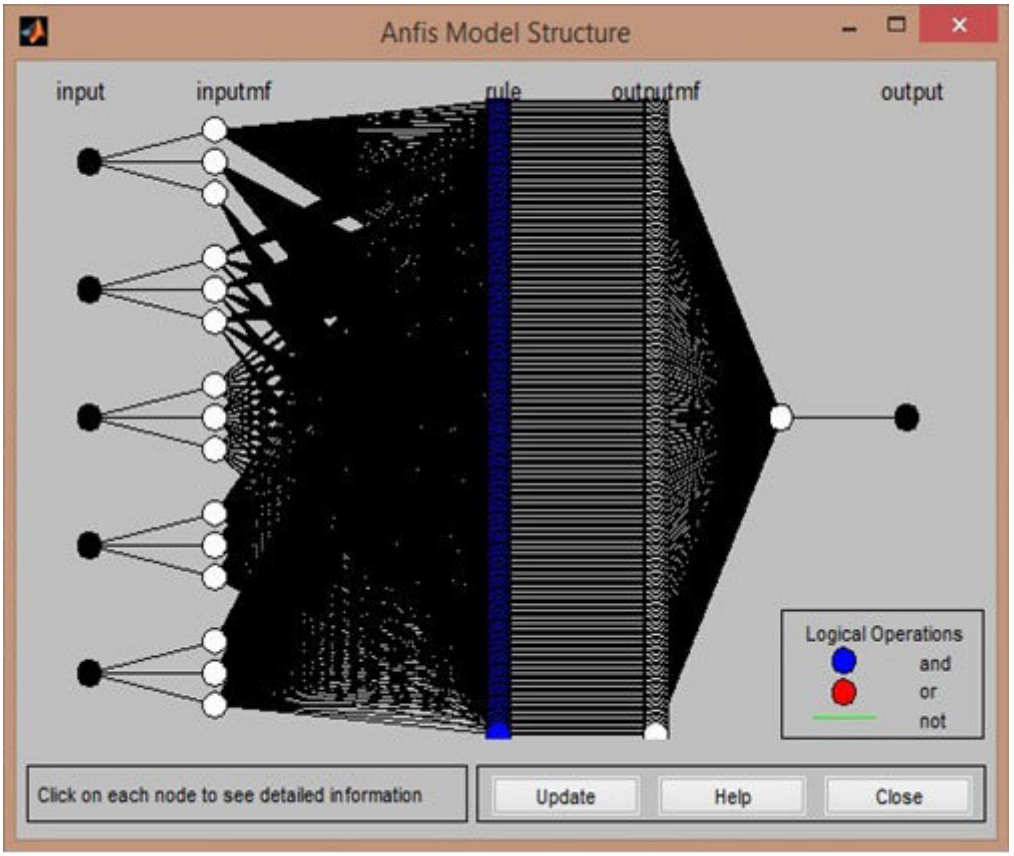


Figure 7.36: *Structure window in ANFIS editor window (MATLAB)*

Edit—FIS editor (to change the name and range):

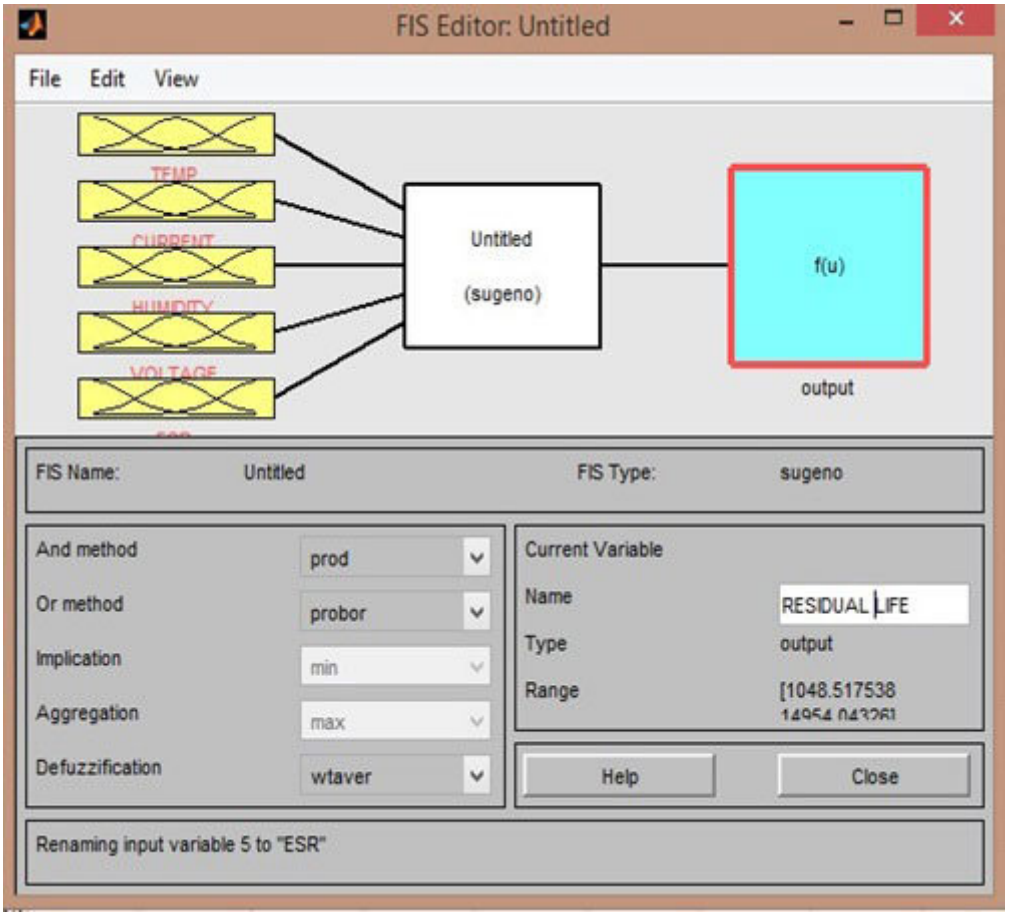


Figure 7.37: *Edit FIS in ANFIS editor window (MATLAB)*

Edit—membership function:



Figure 7.38: *Edit FIS data (MF) in ANFIS editor window (MATLAB)*

Edit—rules:

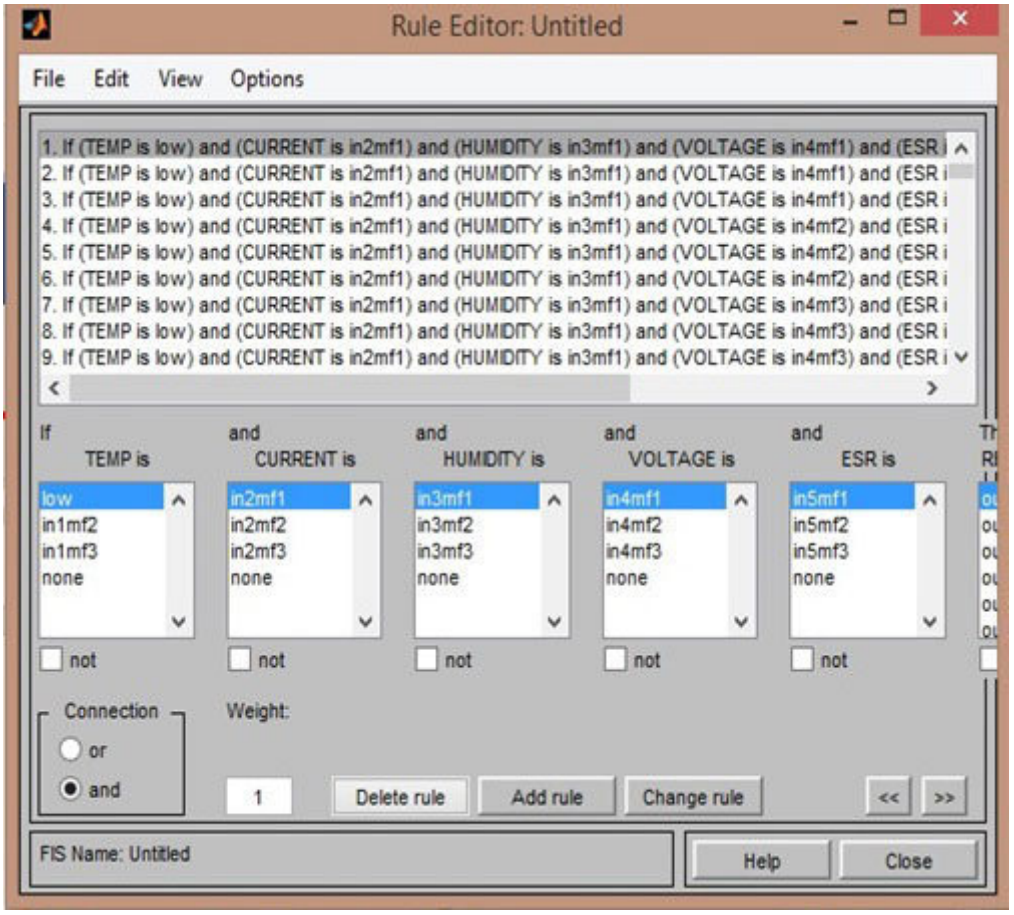


Figure 7.39: *Rule edit in ANFIS editor window (MATLAB)*

View—surface:

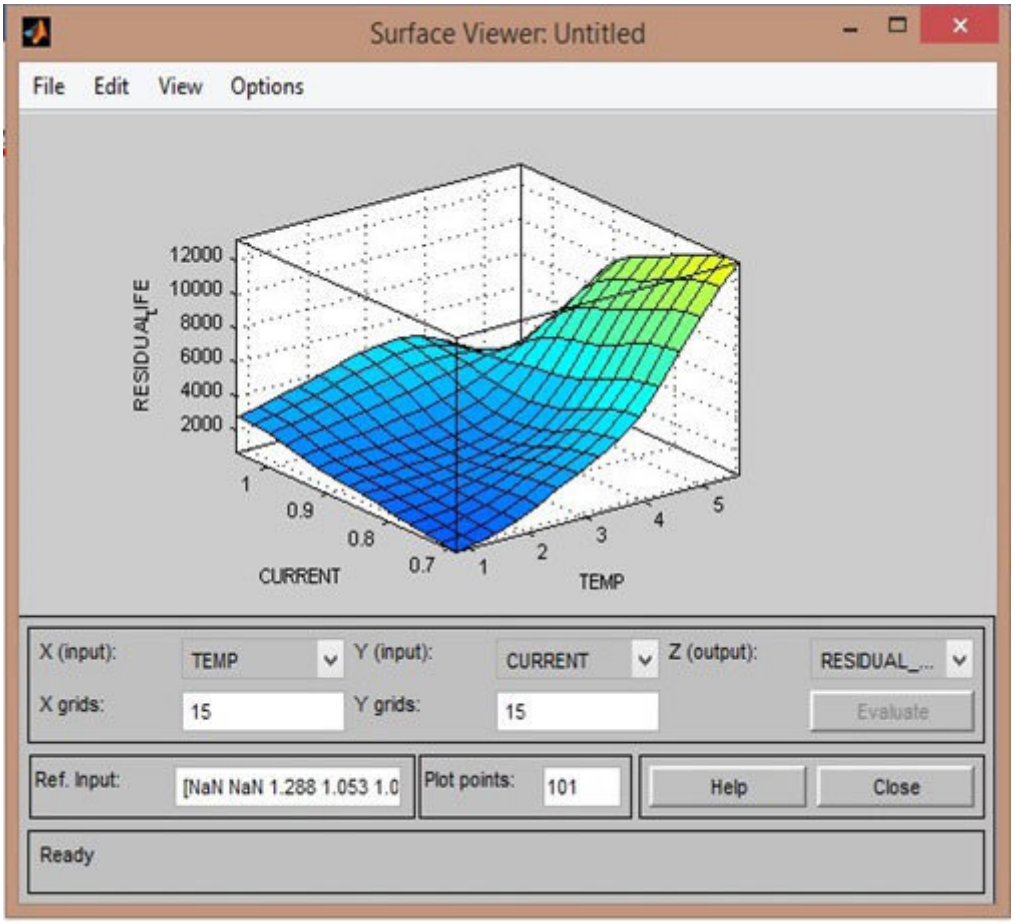


Figure 7.40: *Surface viewer in ANFIS editor window (MATLAB)*

View-rule (for output values):

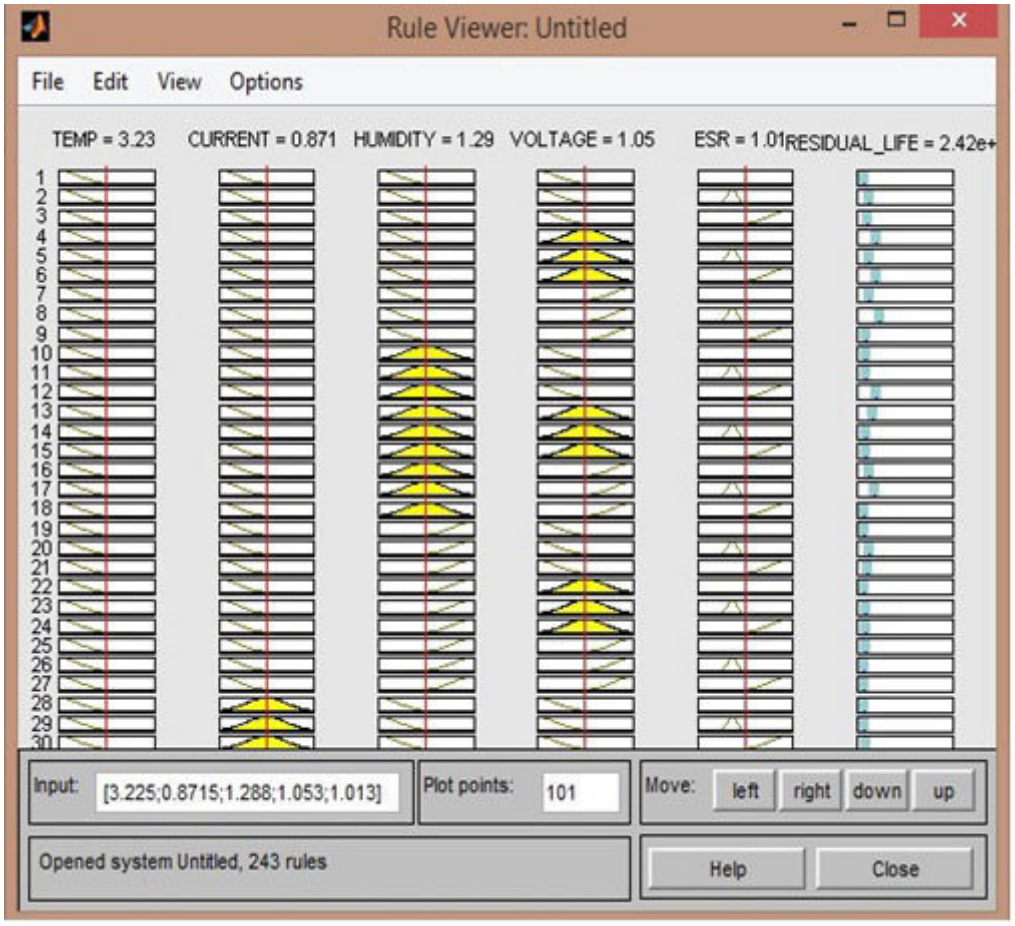


Figure 7.41: *Rule viewer in ANFIS editor window (MATLAB)*

You can get the new output by changing the input.

Conclusion

In this chapter, the step wise use of the MATLAB tool for ANN, Fuzzy, and ANFIS are depicted in detail. The case study of an electrolytic capacitor is elaborated with the help of the MATLAB tool. The step wise process for the health prognostics of an electrolytic capacitor, using the artificial neural networks, fuzzy logic, and adaptive neuro fuzzy inference system, is discussed with the help of the MATLAB.

Questions

How to the design rules in a fuzzy logic system?

What is the importance of a linguistic variable?

How are the ANN and ANFIS co-related?

What is the difference between the ANN, FL, and ANFIS?

Which tool is used for the intelligent modelling?

What are the commands for opening the ANN, FL and ANFIS?

SYMBOLS

555 Timer IC
about 138
experimental testing 140

A

accelerated life testing
importance 102
accuracy estimation and error analysis 122
achieved availability 36
Actuator nodes
about 17
centralized decision-making architecture 18
distributed decision-making architecture 18
Adaptive Neuro Fuzzy Inference System (ANFIS)
about 86
architecture 87
electrolytic capacitor case study 94
fuzzy rules 90
gaussian membership function plots for ESR 89
gaussian membership function plots for humidity 89
gaussian membership function plots for ripple current 88
gaussian membership function plots for temperature 88
gaussian membership function plots for voltage 89
neuro-fuzzy input coded form 91

Sugeno type fuzzy model 88
Advisory Group on Reliability of Electronic Equipment (AGREE) 2

analytical approach, for failure prediction of electrolytic capacitor
about 112
error analysis
application area, of reliability
about 24
mechanical reliability 25
power system reliability 25
robotics reliability 25
software reliability 25
structural reliability 25
artificial intelligence based model 146
Artificial Neural Networks (ANN)
about 78
structure 79
artificial neural network technique 78
availability
about 34
achieved availability 36
expected profit 39
inherent availability 36
mean availability 36
Mean Time Between Failure (MTBF) 38
Mean Time Between Maintenance (MTBM) 38
Mean Time to Failure (MTTF) 37
Mean Time to Repair (MTTR) 37
operational availability 37
point availability 35
sensitivity analysis 39

steady state availability 36

B

bath-tub curve 40
behaviour analysis, of electrolytic capacitor
about 62
effect of ESR 65
effect of humidity 65
effect of ripple current 64
effect of temperature 63
effect of voltage 64
bipolar junction transistor
about 133
experimental testing 133

C

carbon film resistor
about 129
experimental testing
case study, of electrolytic capacitor
about 93
failure prediction, mathematical model used 73
failure prediction, using adaptive neuro-fuzzy inference system model
fuzzy logic model, training 95
lifetime calculation, using fuzzy logic model 95
lifetime calculation, using neural networks 94
lifetime prediction, using regression 74
catastrophic failure

causes, of failure of system

catastrophic failure 42
common cause failure 42
defects, in designing of component 41
human error 42
major failure 41
minor failure 42
operating conditions 41
centralized decision-making architecture 18
common cause failure 42
component reuse
about 54
bathtub curves 55
merits 55
conditional failure intensity 43
configuration, reliability analysis
about 7
mixed configuration 10
parallel configuration 10
series configuration 7
constraints, Wireless Sensor Networks 16

D

Data Acquisition
modes 19
decision support system (DSSRL)
about 92
flow chart 92
for electrolytic capacitor 93

distributed decision-making architecture 18
DOE approach 103

E

electrolytic capacitor
about 127
behaviour analysis 63
experimental testing 129
fishbone diagram 62
mathematical modelling
electronic components
failure prediction 56
reliability testing 124
electronic components failure modes and mechanism 47
empirical methods, for RUL 71
error analysis, of failure prediction models
expected profit 39
experimental approach, for failure prediction of electrolytic capacitor
about 102
DOE approach 103
materials and methods 103
experimental approach, for failure prediction of humidity sensor 116
experimental testing. *See* reliability evaluation
experiments
cautions 142
observation tables 143

F

factors of reliability
adequate performance 32
operating conditions 33

probability 32
specified time 33
failure
about 40
causes 41
reliability measures 4
role of probability laws, in reliability theory 3
failure density 43
failure density function [f(t)] 6
failure frequencies
about 42
conditional failure intensity 43
failure density 42
failure rate 43
failure in time (FIT) 117
failure modes
catastrophic failure 40
initial failure 40
wear-out failure 40
failure prediction
importance 54
failure prediction, of electronic components
about 56
key factors 56
failure rate 43
fuzzy logic technique

about 79
basic structure 80
fuzzy model 81

membership function for current 81
membership function for ESR 82
membership function for humidity 82
membership function for residual life 83
membership function for temperature 81
rules 85
triangular membership function 81

H

hazard function [h(t)] 6
hazard rate
human error 42
humidity sensor
about 115
failure prediction
humidity sensor DHT11
about 124
experimental testing 125

I

inherent availability 36
initial failure 40
intelligent model 78
intelligent model, for reliability prediction 77
intelligent modelling, for reliability assessment

MATLAB used 145

L

Laplace transform 46
longevity 3

M

maintainability 34
maintenance prevention
about 43
electronic components failure mode and mechanism 51
Laplace transform 46
main objectives 43
Markov model 43
methodology 43
reliability analysis, need for 47
supplementary variable technique 45
major failure 41
Markov model
about 43
assumptions 44
Markov graph 44
mathematical model
about 61
electrolytic capacitor 61
mean availability 36
Mean Time Between Failure (MTBF) 38
Mean Time Between Maintenance (MTBM) 38

Mean Time to Failure (MTTF) 37
Mean Time to Repair (MTTR) 37
minor failure 42
mixed configuration, reliability analysis
about 10
parallel-series configuration 11
series-parallel configuration 11

modes, of Data Acquisition
Event Based Data Acquisition 19
Hybrid Data Acquisition 19
Periodic Data Acquisition 19
Query Based Data Acquisition 19

N

Network Latency Time (TNLT) 24
non-repairable system 40

O

operational amplifier
about 140
experimental testing 141
operational availability 37

P

parallel configuration, reliability analysis 10
parallel-series configuration

PN junction diode
about 131
experimental testing
point availability 35
probability of survival 4
public switched telecommunication network (PSTN) 31

R

reliability
about 34
application areas 24
definition 31

scope 31
reliability analysis
about 30
configuration 7
need for 47
reliability analysis, of Wireless Sensor Networks
about 14
data acquisition systems 15
reliability assessment
Adaptive Neuro Fuzzy Inference System (ANFIS), using
ANN, using
fuzzy logic, using
reliability engineering 30
reliability evaluation
555 Timer IC 138
bipolar junction transistor 133
Carbon Film Resistor 129

cautions 142
electrolytic capacitor 127
humidity sensor DHT11 124
observation tables 142
operational amplifier 140
PN Junction diode 131
temperature sensor LM35 126
thermistor 134
thyristor 136
reliability measures
about 33

failure density function [f(t)] 6
failure rate or Hazard rate 5
hazard function [h(t)] 6
Mean Time Between Failures [E(T)] 5
probability of survival 4
reliability of data acquisition 20
ReliabilityRel(t) 33
reliability theory
about 1
role of probability laws 3
reliable data acquisition
about
issues 24
traditional definition 20
repairability 3
repairable system 40
role of probability laws, in reliability theory
hazard rate 4
Weibull distribution 4
RUL prediction techniques

about 56
collection, of failure data 58
comparison 61
component for failure assessment, selecting 57
empirical methods 71
experimental technique 57
failure prediction, using artificial intelligence techniques 60
intelligent model 57
statistical technique 69

S

satellite communication system 30
sensitivity analysis 39
series configuration, reliability analysis
series-parallel configuration, reliability analysis 11
statistical technique 69
steady state availability 36
supplementary variable technique 45
survivability 2
systems
about 39
non-repairable systems 40
repairable systems 40

T

Taguchi approach
about 104
factors assignment, to columns 107

failure time analysis 110
selection of appropriate orthogonal array 106
selection of factors for study 104
selection of number of levels for factors 104
test, conducting 109
temperature sensor LM35
about 126
experimental testing 127
thermistor
about 134
experimental testing 136
thyristor

about 136
experimental testing 137
triangular membership function 81
trouble proofness 2

U

unreliability 34

W

wear-out failure 40
Weibull distribution 4
wireless communication 31
Wireless Sensor Networks
constraints 16
evolution, of Wireless Sensor and Actuator networks 17
methods 16

modes, of Data Acquisition 19
reliability analysis 14
reliable Data Acquisition 20
Wireless Sensor Nodes 17