Chapter 5

Probabilistic Evaluation and Design Aspects for Reliability Enhancement of Induction Motor

5.1 Introduction

The Induction motors are widely used in industrial applications because of simple constructions and their reliability analysis is indispensable. This machine is a mature product with well-established design and thorough analysis. The design of an induction motor is a tedious process and complex that requires theoretical knowledge, working experience, laboratory experiments, many iterations, and verifications before achieving the final acceptable results. These motors have experienced a long life and a high efficiency in service with appropriate design, and quality control. However, reliability quantification is an important and necessary aspect for customer satisfaction, vendor selection, marketing, design improvement, service life determination, production plan, scheduled maintenance, condition monitoring, and fault diagnosis [204]. The work of the designer is guided by industry and international standards that provide standardized specifications relating to machine construction, cooling, safety, performance, testing and reliability for the industrial machine [205, 206]. The electric motors are subjected to increased demand for higher horsepower per frame size, higher operating temperatures, more demanding duty cycles, higher starting currents, constant voltage transients, and severe environmental exposure in the past years. The fault modes of induction machines are very complex so that literatures are plagued to establish the fault evidence for reliability evaluation. The mechanism, effect, maintainability, and maintenance cost of each fault is distinct, so that, in the reliability test, the evidence and targets usually are different for different fault mode [207, 208]. The purpose of reliability testing is to explore the potential problems with the design of an induction motor as early as possible and to provide correct information that the motor meets its reliability requirements. The complex system comprising of induction motor is tested at component, circuit board, unit, assembly, sub-system, and system levels.

The induction machines have excellent reliability. On the other hand, they have several maintenance problems. As a matter of fact, these failure and maintenance result in an excessive maintenance cost per financial year. The maintenance of an induction machine is either based on a traditional maintenance schedule or non-scientific asset management of equipment repair or replacement [209, 210]. The reliability evaluation of induction machines is required to reduce the financial burden. In this context, the cause of failures must be determined and minimized to improve the reliability of induction machines [211, 212]. The reliability improvement is still an important and necessary factor for customer satisfaction; hence it is required to evaluate the reliability of the machine for continuous operation in the midst of the occurrence of the industrial fault [211, 214]. The prime focus of reliability is one of the major factors behind the planning, design improvement, service life determination through advance development; offer the potential of increased motor and power plant component reliability [215, 216]. The Reliability evaluation in this chapter deals with the maximum likelihood of the induction motors to operate in the prescribed period satisfactorily. The induction motors reliability is improved by reducing the causes of failures [217-219].

The important aspects of reliability evaluation and product design related to induction motor are based on the current knowledge of predictive condition monitoring and compliance technologies. To develop and implement the proactive plans to eliminate maintenance requirements at the time of design redundancy, parts de-rating, performance analysis, cost-effectiveness, reliability estimations, and FMEA (failure mode and effect analysis) should be considered. Finally, various types of the test must be performed for ensuring the reliability of the induction motor during pre-production [220]. Many mathematical concepts are applied to reliability engineering, particularly from the areas of probability and statistics evaluation [221, 226]. The product reliability is quantified as MTTF (mean time to failure) for non-repairable product and MTBF (mean time between failure) for the repairable product [222, 223]. Reliability also helps in improving the uptime and productive capacity of critical equipment using formalized problem-solving techniques [222].

Reliability specifications based on life parameters of induction motor must be framed in relation to the appropriate life distributions. Two common parameters used are being used based on analysis of MTBF, when a constant failure rate is assumed, and B-life, related to Weibull life distributions. Specified life parameters must clearly state the life characteristics. For reliability evaluation of induction motor exponential distribution is widely applied for its brevity and simplicity [224, 225]. The different faults on induction machines may produce drastic consequences like product quality of an industrial process where safety aspects of the industry are necessary. The reason for such faults may reside in small errors during motor manufacturing, improper use, high level of requirements in motor start-up, and ventilation deficiency.

This chapter is organized as follows: Section-5.1 presents an introduction to performance evaluation and reliability improvement techniques of an induction motor. Section-5.2 describes the basics probabilistic distribution for reliability estimation and industrial failure modes of induction motors. The reliability indices evaluations using industrial data are included in Section 5.3. The MTBF and failure rates based on industrial data are described in this section. Section 5.4 presents the suggestive methods to avoid failures in induction machines for reliability improvements. The conclusion and discussion are subsequently discussed in Section 5.5.

5.2 Industrial Failure Modes of Induction Motors

The failure of an induction motor may yield an unexpected interruption in the industrial plant which affects product quality, cost, and safety. There are various types of failure modes of induction motors during the industrial applications. First of all, various types of failure modes and their causes have been identified to provide technological suggestions to avoid these causes of failure and eventually to increase the reliability of induction machines. A partial list of such causes of failure that would include as

(i) the opening or short circuit of one or more of a stator phase winding,

(ii) the improper failure for unfavourable environment,

(iii) the unbalanced or fluctuating voltage,

(iv) the poor maintenance practices,

(v) the misalignment or vibration,

(vi) the wrong connections.

5.2.1 Probabilistic Distributions for Reliability Estimation of Induction Motor

The probability, adequate function, time period and operating condition are essential attributes of the system reliability. Probabilistic distributions like Gaussian distribution, exponential distribution, and Weibull distribution are used to model the equipment longevity. The exponential distribution is a suitable candidate for reliability evaluation of the induction motor. The elegance of this distribution is widely applied to reliability engineering for its brevity and simplicity. In practice, distribution functions having monotonic hazard functions seem most realistic to provide the most reasonable models of device reliability. The most common choice of life distribution models for reliability estimation of the components or industrial systems are described in section 5.1.1 and 5.1.2 [223].

5.2.1.1 Exponential Distribution based Probabilistic Evaluation

The exponential distribution based probabilistic evaluation is the most widely used distribution function for reliability and maintainability modeling. It is a popular model of component reliability evaluation because it is algebraically simple and thus tractable. It is considered as the representative of the functional life interval of the device life cycle. Any component is expected to function satisfactorily before reaching the wear out period, in this regards an appropriate model of component reliability is one having a constant hazard rate [228]. Detailed discussion and genesis of concepts on exponential distribution are discussed in [223]. The induction motor reliability and MTBF of series and parallel connected components are evaluated using exponential probabilistic model [220, 221].

5.2.1.2 Weibull Distribution based Probabilistic Evaluation

The Weibull distribution is one of the most important lifetime distributions and illustrated the failure times of components when their failure rate either increases or decreases with time such that it follows the reliability function associated with the Weibull failure time distribution [224]. It is found that such distribution provides a reasonable model for the life length of many devices like an industrial induction motor. The Weibull distribution has advantages of flexibility in modeling various types of hazard behavior and algebraic tractability. Also, the Weibull distribution is one of the possible realizations of the extreme value distribution as demonstrated in [228] and as with any two-parameter distribution, it can be made to fit with many actual situations reasonably well. The data are consistently analyzed using statistical techniques such as Weibull analysis and linear regression to ensure the system reliability meets industrial requirements [220, 222, 226]. The induction machine operates in motoring as well as generating modes of applications. It is an important component of an electrical power system due to the following facts that the reliability of the power system dependent upon the reliability of an induction motor.

5.2.2 Hazard Model for Life Distribution of Induction Motor

To establish the distribution of the motor's life, a large-scale technical survey has been made. According to the statistical data, the curve of the motor's fault rate v/s time is drawn. In this curve, the motor's life can be separated into three periods: early failure period, constant failure period and wear-out the failure period. In the early life of a motor adhering to the bathtub curve, the failure rate is high but rapidly decreasing as defective parts are identified and discarded and early failures of a motor such as handling and installing error are overcome. The author estimate that the motors in worksite commonly operate in the constant failure period. In this period, the motor's fault rate is constant and its life belongs to a single-parameter exponential distribution. In the middle life of a motor, the failure rate of the motor is low and constant. In the later life of the motor, the failure rate increases, as age and wear tear take takes place on the motor. Because of the shape of this failure rate curve, it has become widely known as the "Bathtub" curve as shown in Figure 5.1 [227] and all the Induction motors' life cycle analyzed from Bathtub curve. The initial region that begins at time zero when a customer first begins to use the product is characterized by a high but rapidly decreasing failure rate. This region is known as the Early Failure Period [221]. The failure rate level off and remains roughly constant for the majority of the useful life of the motor. This extended period of a level failure rate is known as the intrinsic failure period (also called the stable failure period). Note that most of the motors spend most of their lifetimes operating in this flat portion of the hazard model. Finally, if motors from the population remain in use long enough, the failure rate begins to increase as materials wear out and degradation failures occur at an ever-increasing rate. This is considered as the wear-out failure period [228].

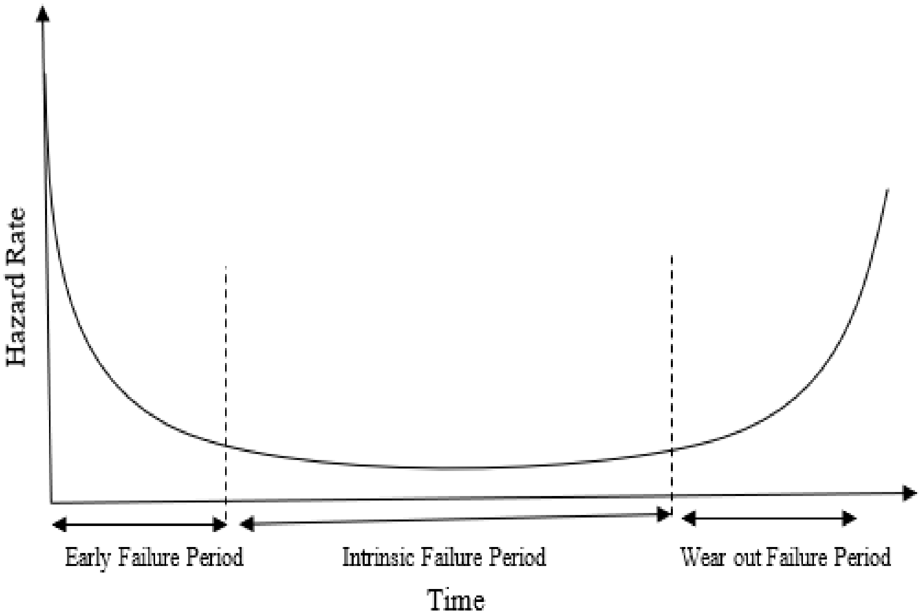

Figure 5.1: The hazard model of induction motor

5.2.3 Major Fault Modes of Induction Motor

The failure of an induction motor creates an unexpected interruption in the industrial process with consequences in product quality and plant safety. By virtue of appropriate design and quality control as discussed in previous sections, these motors have experienced a long life and a high efficiency in service. But reliability quantification is still important and necessary for customer satisfaction, marketing, vendor selection, design improvement, service life determination, production plan, and scheduled maintenance. To analyze the primary failure modes and their effects, the faults of the motor are classified [218]. The statistical studies of IEEE and Electric Power Research Institute (EPRI) for motor faults are illustrated in details [229].

Class A: The critical faults caused by inherent weakness due to failures of electric insulation or the main structural part of induction motors are

(i) failure of electrical insulation system,
(ii) misalignment of rotor that touches on stator,
(iii) failure of frame and end cover,
(iv) failure of rotor bars or cracked rotor end rings,
(v) broken shaft,
(vi) failure of excitation,
(vii) LIR (low insulation resistance) value of the components, and
(viii) circulating currents on bearing.

Sornmuang and Huang [230, 231] have explained the motor bearing shield fault and rotor eccentricity faults in a remarkable manner.

Class B: The major faults, which causes a minor failure or cause less damage to the operation of the motors and can be repaired by replacing some components. For repairing these faults, less time and less cost are required. These types of major faults are

(i) failure of terminal box,
(ii) failure of wiring box,
(iii) failure of fan,
(iv) failure of bearing,
(v) loss of rotor’s balance pieces,
(vi) static or dynamic air gap irregularities.

Above explained faults may be observed through some of the symptoms as [218]:

(i) unbalanced air gap voltage, and line currents,

(ii) increased torque pulsations,

(iii) increased average torque,

(iv) increased losses

(v) excessive heating.

The maximum warranty period provided by industries is three years, but 74% of failures are observed during the warranty periods as shown in Figure 5.2. The maximum failures are obtained in the year 2012-2013 as seen in the chart sheet of Table 5.1 and the bar chart representation is also shown in Figure 5.3. The industrial data are collected to study the types of failure in the prescribed financial year. The types of failures are shown in Figure 5.4. According to the number of failures, motors are manufactured in the same proportionate as given in Table 5.2 and also represented with the help of bar graph in Figure 5.5.

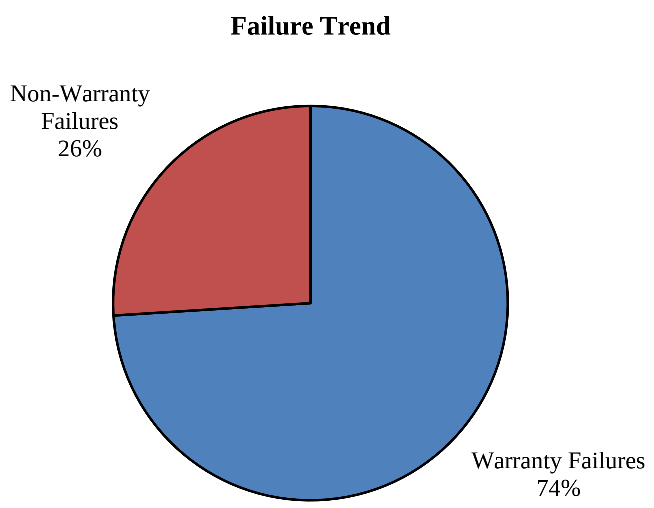

Figure 5.2: Warranty failure of induction motor

TABLE 5.1: Number of complaints or failure trend/year

Sr. No.	Year of complaint	Number of motors failed
1	2007-2008	95
2	2008-2009	117
3	2009-2010	129
4	2010-2011	123
5	2011-2012	144
6	2012-2013	276
7	2013-2014	163
8	2014-2015	179
9	2015-2016	173
10	2016-2017	140
11	2017-2018	137

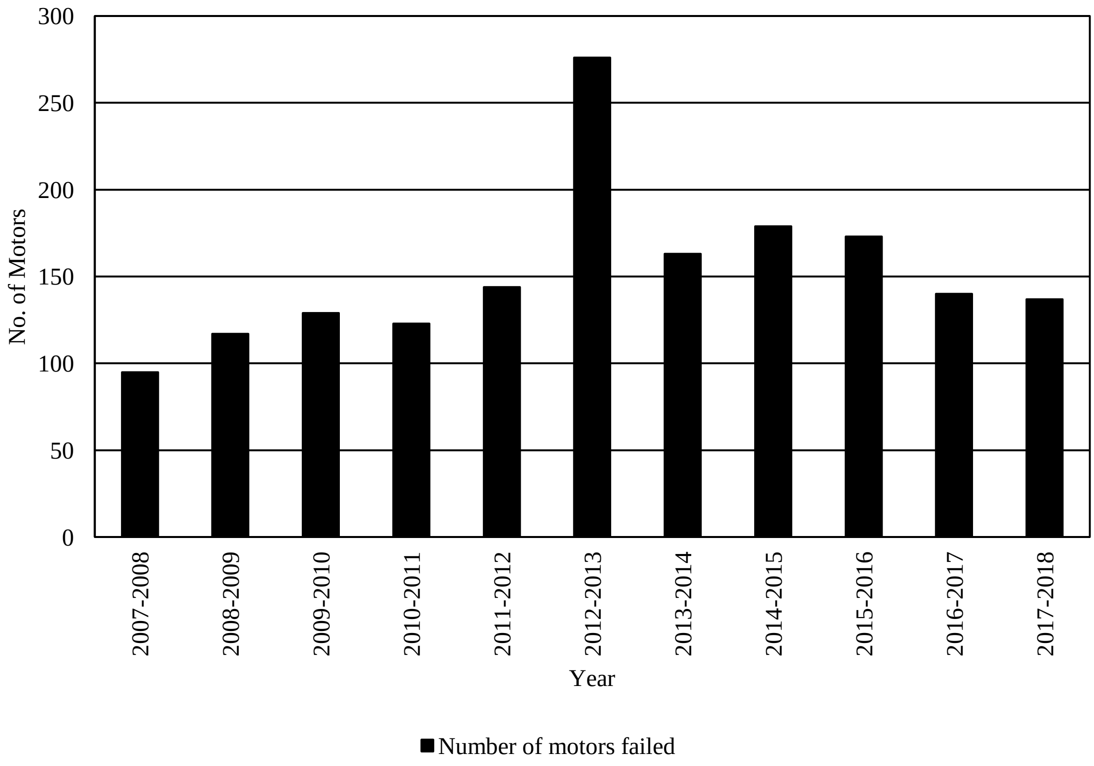

Figure 5.3: Number of motors failed during 2007-2018

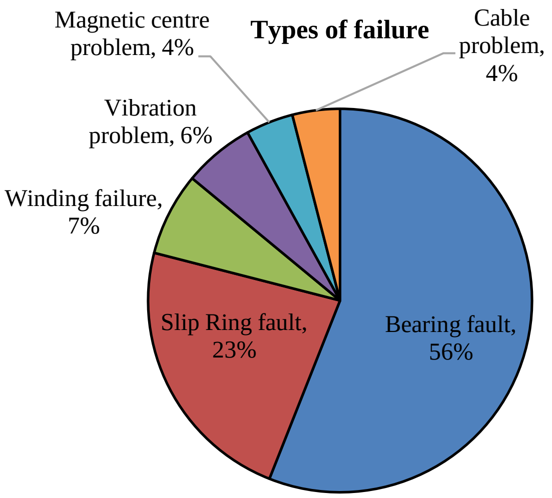

Figure 5.4: Types of failure in induction machine in the year 2012-2018

TABLE 5.2: Number of motors manufactured

Sr. No.	Years of manufacturing	Number of motors manufactured
1	2007-2008	1302
2	2008-2009	1358
3	2009-2010	1536
4	2010-2011	1721
5	2011-2012	1879
6	2012-2013	1477
7	2013-2014	1633
8	2014-2015	1754
9	2015-2016	1864
10	2016-2017	1996
11	2017-2018	2023

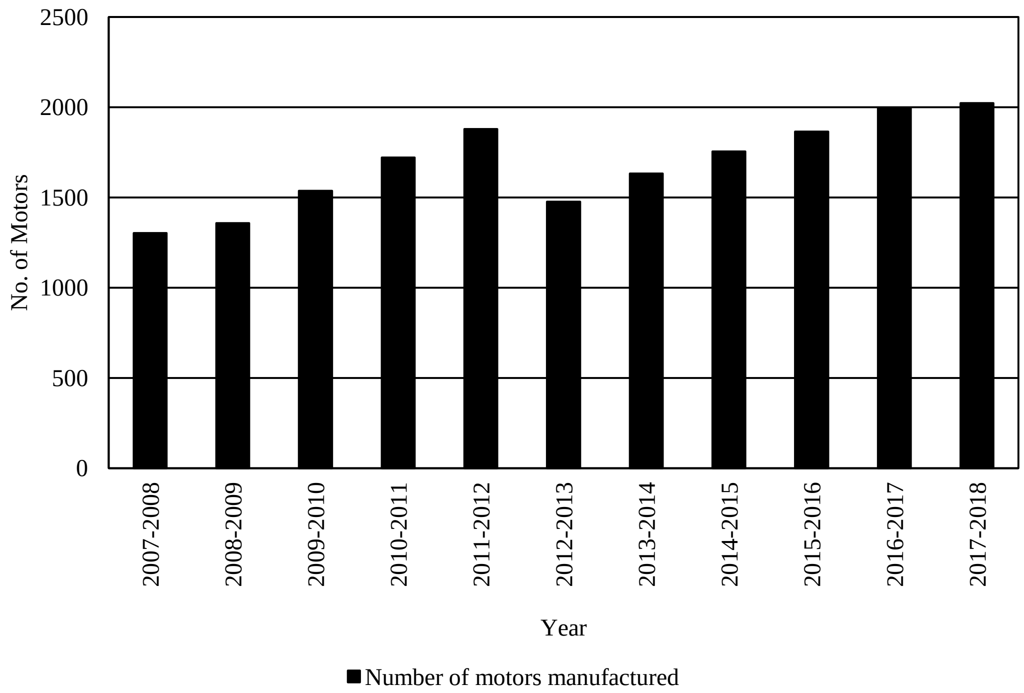

Figure 5.5: Number of motors manufactured during 2007-2018

5.3 Reliability Aspect and MTBF Evaluation using Industrial Data

The reliability of an induction motor is the survivor rate of the product under defined performance functions and a defined environment. Such product reliability is required for developing reliability of any machine, evaluation of engineering changes and validation of problem resolutions. The reliability prediction in such situations becomes an integral part of the reliability planning and designing. A reliability prediction always accompanies the reliability specifications and both will be achieved with good reliability data. The MTBF is the universal measure of reliability considering the constant failure rate. The failure rate remains constant only when failed components or equipment is replaced as and when required during useful life period. Estimating the failure time distribution or long term performance of the induction motor of high-reliability products is particularly difficult. The induction motors are designed to operate without failure for years, decades or even longer.

The methods and evaluation steps employed over the years to determine the MTBF are

(i) to conduct the life testing in a controlled laboratory environment over an extended period of time;

(ii) to field-test a large population of motors over an extended period of time in a number of different environments;

(iii) to use empirical data from a sufficient field sample size to conduct a statistical analysis;

(iv) to conduct a FMEA on a new design and compare with existing designs that have proven field performance that can be used as a benchmark and

(v) to analyze field failures and warranty data after units have been in operation for a longer duration to retrieve meaningful.

The MTBF is the measure of product reliability to perform its function adequately. The unit of MTBF is usually expressed in hours; the higher value of MTBF denotes the higher value of the reliability of the product. The MTBF is termed as the ratio of total time and number of failures. If the MTBF of the component is known, the failure rate can be calculated which is the reciprocal of the MTBF. Once the MTBF is calculated, the probability that the machine will work for time t without failure is described by $P\ (t)\ =\ e^{-\left(\frac{t}{MTBF}\right)}$. When time (t) equals to MTBF, the probability that machine will survive to its calculated MTBF becomes 36.8%. For reliability evaluation of the production rate of induction motors, the failure trend data are needed for subsequent analysis. The authors have collected ten years of industrial data related to machines manufactured and the number of failures of the machine on a yearly basis. The name of the production company is not mentioned in this chapter due to security reasons. By using the industrial data of Tables 5.1 and 5.2, MTBF, failure rate and reliability of induction motor are evaluated in Section 5.3.1. Finally, the reliability improvement methodologies have been suggested in Section 5.3.2.

5.3.1 Reliability Evaluation of Induction Motor

The reliability operational assessment methods of induction motor are based on failure reporting analysis and corrective action system. This systematic approach develops reliability, safety, and logistics assessment based on failure reporting, management, analysis, and corrective/preventive actions. This method is adapted to create a failure data repository from which statistics are derived due to accurate and genuine reliability, safety, and quality performances. The overall output from these evaluations is MTBF, MTTR, spares consumption, reliability growth, incident distributions by type, location, part numbers, series numbers, symptoms, etc. as described in Section 5.4. The MTBF is usually evaluated for one year of operation in the previous research works. The time in hours will be 365 x 24 = 8760 hours. The reliability of the induction motors for three years of operation is evaluated in this chapter. The period for three years in hours will be 365 x 3 x 24 = 26280 hours. The reliability indices evaluation for the financial year 2007- 2008 are MTBF = (1302 x 8760) / 95 = 120058.1053;

Failure rate = 1/ 120058.1053=8.329 $\times 10^{-6}$

and

$Reliability\ =\ e-(26280)\ \times\ (failure\ rate\ for\ the\ year)$ = 80.34%.

Similarly, the reliability indices evaluation of motor is done for 10 years of operation from 2008 - 2009 to 2017 - 2018 as mentioned in Table 5.3.

Table 5.3: Reliability indices of induction motor

Sr. No.	Years	MTBF in hours	Failure Rate in per hour	Reliability in %
1	2007-2008	120058	8.32931E-06	80.34%
2	2008-2009	101676	9.83516E-06	77.22%
3	2009-2010	104305	9.58727E-06	77.72%
4	2010-2011	122569	8.15867E-06	80.70%
5	2011-2012	114306	8.74845E-06	79.46%
6	2012-2013	46879	2.13315E-05	57.08%
7	2013-2014	87761	1.13946E-05	74.12%
8	2014-2015	85642	1.16765E-05	73.62%
9	2015-2016	94385	1.05949E-05	75.69%
10	2016-2017	124893	8.00685E-06	81.02%
11	2017-2018	129354	7.73072E-06	81.61%

From Table 5.3, the reliability of operation of the machines under warranty period is less than 80%, which is not suitable for the industrial machines, where the continuous operation of machines is needed and the corresponding bar chart representation is shown in Figure 5.6 (a) and (b) for the Table 5.3. As the failure rate is decreasing the reliability of the induction motor increases as shown in data given in Table 5.3. The reliability is least for 2012-2013 due to increment in a number of failures and highest for 2017-2018 as the number of failures reduced which is noteworthy to mention. The failure of the machine during the warranty period is 74%. The industrial data of the years from 2007 to 2018 are analyzed to draw the reliability indices (reliability, MTBF and failure rate) versus hours of operation graphs for the period of 10 years. To decide the maintenance schedule for the machine and also whether a stand by the unit is needed or not depends upon the requirement of the operation are described in the next section of this chapter.

Figure 5.6: (a) Reliability v/s MTBF of induction motor

Figure 5.6: (b) Reliability v/s Failure rate of induction motor

5.3.2 Reliability Improvement of Induction Motor

The overall improvement of product reliability depends on the reliability design and its associated parameters. The design parameters of induction motors are evaluated on the basis of reliability assessment and the recommendation evolved through the assessment. The induction motor design parameters are component selection, operating conditions, customer specifications, material tolerance, and mechanical strength. As seen from the reliability calculation of industrial data for the year 2008-2009 and 2012-2013, the component reliability for three years of operation is small. The reliability of the machines for the year 2008-2009 is 77.22%, and for the year 2012-2013 is 57.08% which is the lowest among all reliability values. Consider, one machine is operating as a primary unit with 57.08% reliability and a stand-by unit for the same purpose with the reliability of 77.22% for three years of operation. The combined reliability of the two machines is determined to be 89.60% Thus, it is reflected that the probability of continuous working of the machine for three years is increased up to 90%. Since purchasing the standby unit is not a cost-effective technique to improve reliability, the author(s) need to reduce the failures modes that occur in induction machines to improve the reliability.

5.4 Motor Failures and Design Enhancement for Reliability Improvement

The failure modes of induction motor are any errors or defects in industrial process and operational design which affect customer satisfaction. Failure modes, causes, effect analysis and suggestions for reliability improvement of induction motor are described here in detail. The authors have considered some of the techniques and checklists to improve electrical reliability design of induction motor. Appropriate operating temperature, options for de-rated components used, appropriate component selections, use of best design tools, appropriate materials selection, design with a maximum operating margin and understanding with customers' requirements have described for electrical design improvement of induction motor. Similarly, the techniques and checklist for mechanical reliability design parameters are operational mechanical strength, static and dynamic dimensional stability, material adequacy, thermal tolerance, and contamination control. The potential FMEA of induction motor components are illustrated in this section to take actions to eliminate or reduce failures on appropriate priority. Induction motors are reliable in operation but are subjected to different types of undesirable failures. The poor coordination of components, abrupt use of electrical winding and magnetic materials are the main causes of failure in industrial induction motors as reflected in Figure 1.1. The most vulnerable parts for technical faults in the induction motor are bearing, stator, winding, rotor bar, and shaft. Also, the faults on frame cover, terminal box, wiring box, and fan are considerable during the laboratory works. The different types of failures in an induction motor are illustrated in Table 5.4 which follows the statistical studies of IEEE and EPRI for motor faults as given in Figure 1.2 and Figure 1.3. Hence, the failure cases of the industrial induction motor and technological suggestions to minimize the likelihood of failures for reliability, safety, and quality enhancement are illustrated in this section.

Table 5.4: Number of different types of failures

Sr. No.	Years	Bearing Failures	Rotor-Stator Contact Failures	Rotor mass Unbalance	Other Failures
1	2007-2008	38	27	8	19
2	2008-2009	49	35	10	23
3	2009-2010	54	40	11	24
4	2010-2011	56	42	12	29
5	2011-2012	59	51	9	28
6	2012-2013	111	80	19	49
7	2013-2014	67	50	14	32
8	2014-2015	76	59	17	40
9	2015-2016	75	60	13	35
10	2016-2017	62	42	11	26
11	2017-2018	60	44	5	31

5.4.1 Rotor-stator Contact

The three main types of behaviours of induction motors' stator-rotor contacts are experienced during its industrial operations [232].

(a) Forward whirl annular motion: In this case, the rotor is maintained in contact with the stator and sliding occurs during the full operation. The full annular friction generally occurs in a forward whirl at the same speed as that of rotor rotation (forward synchronous whirl). This motion results from the nonlinear response of the rotor due to unbalance.

(b) Backward whirl motion: This configuration in which the rotor is driven in a backward whirl in the stator is initiated by the friction which is induced at the contact interface. The rotor rolls or slides continuously on the contact surface and is subjected to backward whirl at non-synchronous speed.

(c) Rebounds: The partial friction is characterized by discontinuous contact along with precession of the rotor and then repeated rebounds between the rotor and the stator. The rebound configuration can be either permanent or transient. The rotor-stator contacts a serious problem when any part of the moving rotor touches the stationary stator of the machine it may cause damage to both stator and rotor, as shown in Figure 5.7.

The causes of rotor and stator contact failure are due to unbalance in the rotor, the non-uniform gap between stator and rotor misalignment, and bending of the overhang portion of the stator winding. Thus, to avoid the above-mentioned failures the balancing report of the rotor must be checked for proper balancing at the time of assembly. The air gap between the stator and rotor must be measured in different positions with the help of filler gauge shown in Figure 5.8. This will ensure the presence of a uniform gap so that any part of the rotor does not touch the stator due to misalignment.

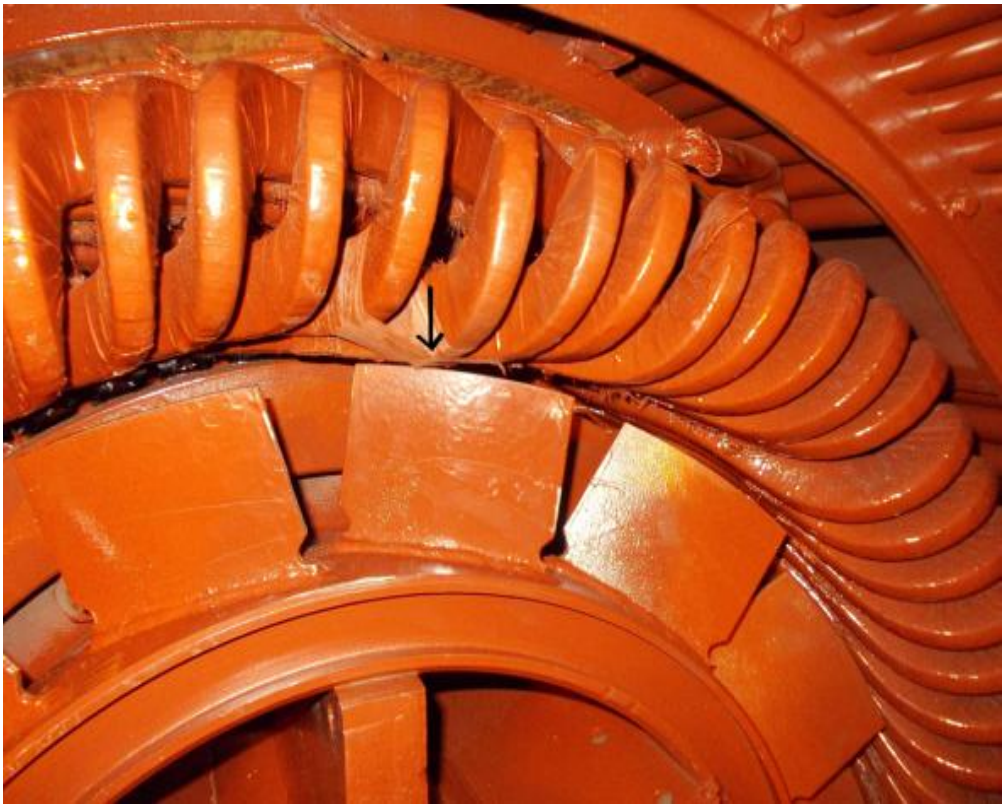

Figure 5.7: Pictorial view of rotor touching the stator winding

Figure 5.8: Pictorial view of Feeler Gauge

5.4.2 Failure of Frame and End Covers

Frame and end covers are important parts of the electrical machine. The stator body is inserted in a frame and locked; the end shield covers are fitted at both the ends of the machine, in which bearings are mounted. The cause of this failure is due to the roughly machined surface or oval shape in the frame which leads to the displacement of the bearing from its actual position. At the time of machining of the frame or end cover, the dialing should be done with the help of dial gauge to be made sure that the machined surface is under the designed limit. At the same time from the dial gauge readings as shown in Figure 5.9, and it can be checked in the presence of oval part in the frame.

Figure 5.9: Pictorial view of Dial Gauge

The dial gauge has two scales one at the outer side marked with (0 - 100) and second at the inner side marked (100 - 0). The outer scale (0 - 100) is used when dial gauge needle moves in the clockwise direction while inner scale (100 - 0) when dial gauge moves in anticlockwise. When the sensor of dial gauge is pushed upwards (towards the dial) then the needle of dial moves clockwise, similarly, when the sensor of dial gauge moves downwards (away from the dial), then the needle of the dial moves in the anticlockwise direction. The dial gauge readings when dial moves in the clockwise direction are taken as positive whereas when the needle moves in the anticlockwise direction taken as negative. The movement of the needle should be watched for clockwise or anticlockwise rotation throughout the periphery of the frame or end shield to introspect any disorder.

5.4.3 Failure of the Terminal Box

The terminal box is on top or either side of the outer cylindrical frame of the stator to get the external electrical connections. Failure of the terminal box leads to sparking, damaging the connecting cables, fire hazards, etc. The causes of the following failure are due to loose connections between connectors and cable, by not maintaining the proper gap between the two phases of cable, poor welding of earthing pad, and having a lower insulation resistance value of a terminal box as shown in Figure 5.10. The technological suggestions are

(i) the insulation resistance of the terminal box should be checked and confirmed that it is up to the mark or not at the time of testing,

(ii) the Proper gap should be maintained between the glands to separate the cables,

(iii) there should be no gap between the connector and the cable as it leads to sparking which eventually damage the cables, and

(iv) earthing arrangement should be checked properly.

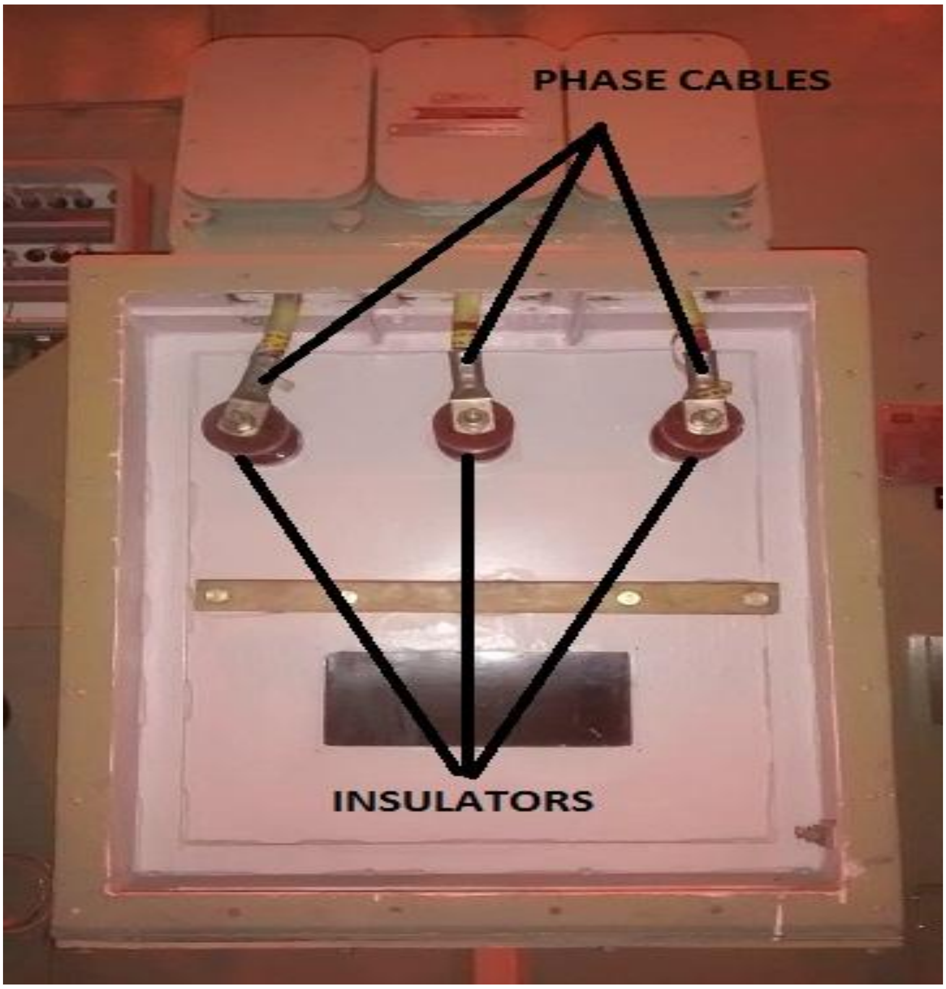

Figure 5.10: Main terminal box

5.4.4 Failure of the Wiring Box

In the wiring box or RTD (a resistance temperature detector) box, the different RTD's are terminated that shows the temperature of different windings present in the stator, the failure of wiring box means the RTD'S are showing false temperature readings of the windings. The cause of its failure is that sometimes at the time of termination, the RTD'S are changed and misplaced from its original position so after assembly it shows the false reading. The technological suggestion to avoid this failure is proper ferrule (marking by numbers or alphabets) numbering should be done so that the RTD'S can be easily identified and can be correctly terminated in the wiring box as shown in Figure 5.11.

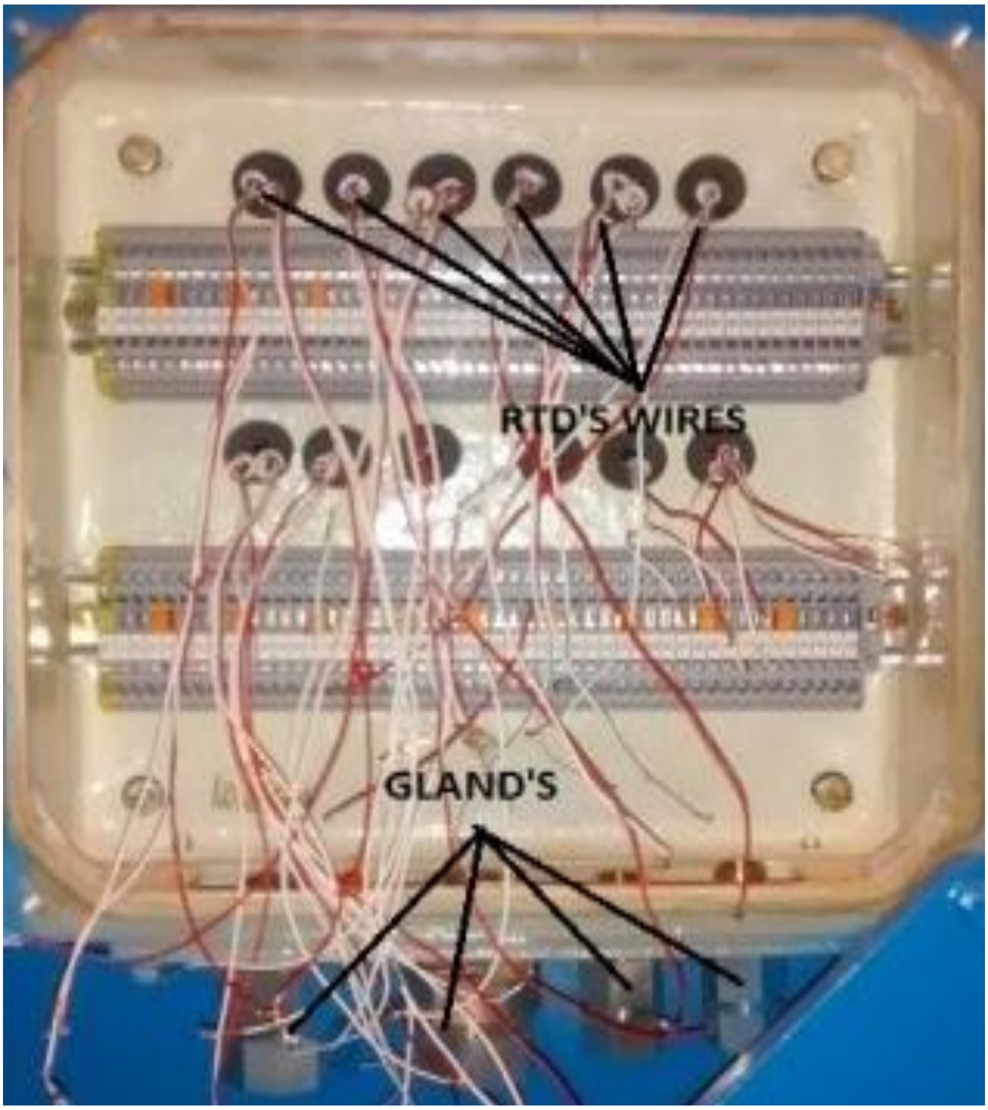

Figure 5.11: Pictorial view of Wiring Box

5.4.5 Failure of Fan

It is normally located at the opposite end of the load side, called the non-driving end of the motor, for forced cooling of both stator and rotor. It serves the purpose of cooling and completes the cooling circuit; if the fan fails, there is a rise in temperature in the machine which may cause overheating of the windings and bearings [212]. The causes of fan failure are due to damaged blades and the wrong direction of rotation. The technological suggestion to avoid these failures is that at the time of testing if there is a sudden rise in temperature which can be detected by ATD mounted on the cooler, immediately shut down the machine is checked. The direction of rotation of the fan and then the air guide arrangement which is meant to guide the air and complete the cooling circuit.

5.4.6 Failure of Bearings

Bearings makes the rotor to properly aligned in place and help it to rotate freely by decreasing the frictions. Motor bearing faults and motor bearing shield fault are explained in [230, 233]. Bearing failures have accounted for an increased percentage of motor failures. In terms of induction motor failure, the bearing is the weakest component of an induction motor. It is the single largest cause of fault in an induction motor. As per the study of IEEE and EPRI, given in Figure 1.2 and Figure 1.3, 41–42 % of induction motor faults are due to bearing failure as described by Singh et al.[229].

The cause of bearing failure are excessive loads, tight fits, excessive temperature rise, fatigue failure, corrosion, contamination, lubricant failure, misalignment are the causes. In operation of electrical machines, undesirable voltages can occur at shafts and bearings, resulting in the generation of damaging currents. These currents can destroy the bearing running surface. There may be other causes like increased load, increased temperature and speed, faulty assembly of bearing components.

The technological suggestions to avoid the bearing faults are as follows:

(i) Shaft voltage: Voltages induced into the shaft through an alternating flux arises because of flux asymmetry of the magnetic circuit. The shaft voltages depend on the dimensions, manufacturing inaccuracies and excitation state of the machine [214]. The over shaft voltage can be avoided by separating bearing with insulation ring and by using insulation bolts which will break the circuit, and the circulating currents will not flow in the surface of bearings. Another method is by using a rotor earthing arrangement as shown in Figure 5.12, this arrangement consists of carbon brushes attached to the copper handle, the copper handle is connected to the end frame and the carbon brushes are continuously making contact with the rotating shaft and in this way we can earth the overvoltage generated in the shaft can be avoided.

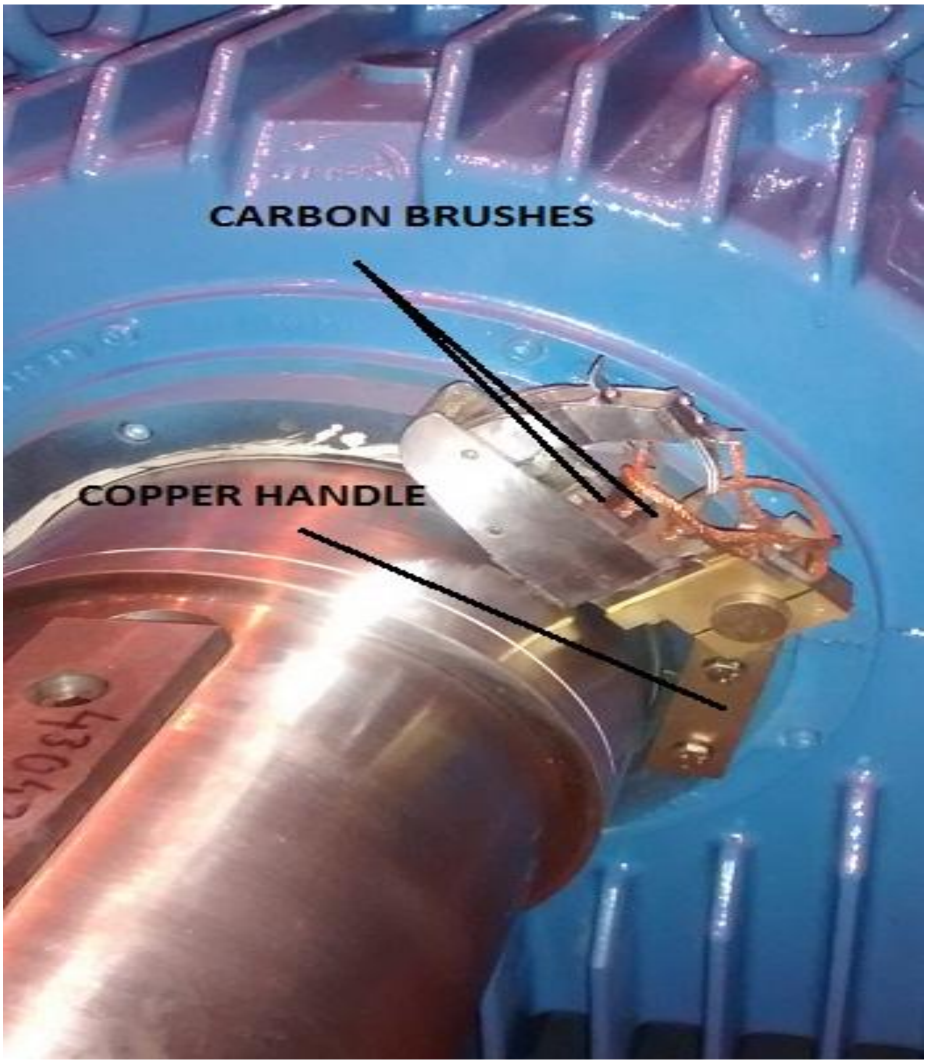

Figure 5.12: Rotor earthing arrangement

(ii) Temperature rise: Calibrated bearing temperature detector should be connected to the bearings so that temperature can be monitored correctly; sometimes small lubrication may be the cause of temperature rise so grease should be properly injected with the help of grease gun as shown in Figure 5.13.

Figure 5.13: Pictorial view of Grease gun

5.4.7 Rotor Mass Unbalance

If the rotor is not centrally aligned or its axis of rotation is not the same as the geometrical axis of the stator, then the air gap will not be uniform and the situation is referred as air-gap eccentricity. Air-gap eccentricity may occur due to any of the rotor faults like rotor mass unbalance, bowed rotor fault, etc. There are three types of the mass unbalanced rotor are [234]:

(i) static mass unbalanced rotor,

(ii) couple unbalance rotor,

(iii) dynamic unbalance rotor.

For balancing the rotor, author(s) need to put individual weights at different locations of the rotor. The cause of this type of failure in an induction motor is mentioned as whenever the rotor rotates at high speed say 1500 rpm to 3000 rpm, weights that are riveted to the rotor sections may become loose over the period and thrown away which may cause considerable damage to rotor and stator windings. The technological suggestion to avoid this failure is that after balancing different weights that are needed to put on different positions of rotor. These weights are riveted on the rotor as shown in Figure 5.14. When these weights are riveted on the different sections at that time, full welding should be done to ensure that these weights may not get loose in the future. The welding done provides necessary strength between the rotor and the weight.

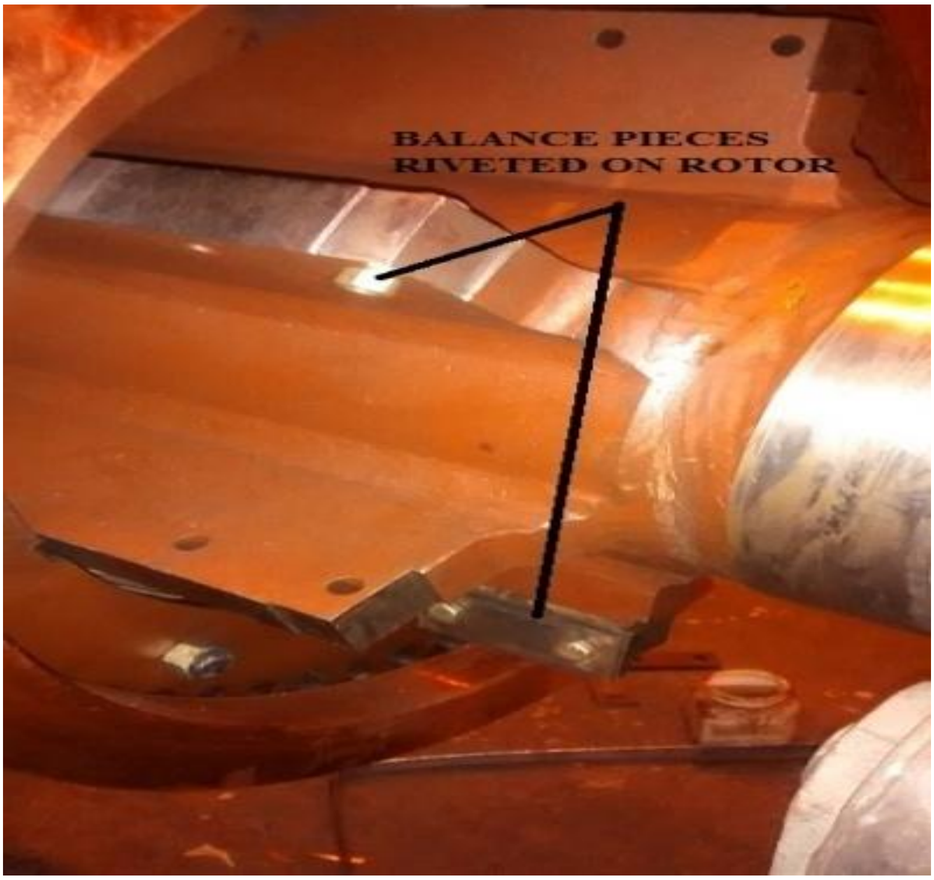

Figure 5.14: Balance pieces riveted on rotor

5.5 Conclusion

The induction motors are frequently used machines in industrial sectors and play a dominant role in many fields. Though industrial induction machines have excellent reliability, yet they have several maintenance problems. Due to failures and maintenance of machines and excessive maintenance cost per financial year increases tremendously. In this chapter, the attempt is made to comprehensively discuss the reliability, MTBF, and failure rate of induction motors have been evaluated with the help of the industrial data. It has also been described mathematically how the purchase of a standby machine increases the reliability of system operation. For various failure modes, preventive and suggestive methods are demonstrated in order to reduce the faults in induction machines. The reliability indices (MTBF, failure rate, adequacy) v/s operational time curve based on probabilistic evaluation has been demonstrated successfully. This curve is very helpful to provide information about the planning maintenance schedules to obtain reliable operation without interruption.