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RELIABILITY ANALYSIS OF INDUCTION MOTOR USING STOCHASTIC MODELING

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ABSTRACT

For every organization the key to its success is to provide reliable products across its entire range and hence reliability analysis becomes an important aspect to improve a brand positioning. Cost of poor quality becomes a critical factor in an organization's profit. This paper deals with the study of failure occurring due to failure of the starting mechanism of the motor that includes the start capacitor, the starting winding and the winding switching switch through a centrifugal gear. Due to the failure interaction between the sub-assemblies the whole scenario becomes stochastic. Using stochastic techniques reliability analysis is carried out. Modeling, analysis and implementation potential of reliability enhancement on the induction motor are discussed in the paper.

KEYWORDS: Reliability Analysis, Markov Model, Semi Markov Model, Method Of Stages, Induction Motor

Reliability assessment of motor drives is essential, especially in electric transportation applications in general. Safety is a major concern in such applications, and it is related to reliability. Specifically, field complaints reveal that single phase induction motors prominently fail in capacitor start and run in fans used in domestic applications. This type of motor uses an open circuit switch to switch-on and off the start capacitor and the auxiliary winding. Initially when the motors start switch is in the closed position which allows the start capacitor and auxiliary winding to be in circuit, which aids in starting of the motor. Once the motor picks up the rated speed the centrifugal gear opens the switch thus disconnecting the OC switches which in turn disconnects the auxiliary and start winding. The switch will again come on when the motor is loaded up to its run up torque load when the speed of the motor drops.

This is done to accelerate the motor again to its rated speed. During this time a very high voltage potential builds up between the two faces of the switch. When the contact does happen a very high current up to 100 Amperes passes for few seconds. When the switch disconnects arcing between the two faces takes place. Due to this repeated arcing process the contact surface gets destroyed the two contact surfaces get fused and the switch does not disconnect. Due to this switch failure, the failure rate of other two components increases drastically since continuous current is flowing through them. After 4 minutes of the switch failure the start capacitor will burst. Then finally due to continuous high current flow, the auxiliary winding burns, and causes a complete motor failure. Thus it demonstrates very high degree of failure interaction between various components because of which the whole scenario becomes stochastic.

PROBLEM ON HAND

The three components of Induction motor viz. starting winding, start capacitor and open circuit switch show that there is a strong correlation between the three components which attributes to the failure of the motor as reliability of the other components drastically drops as one of the components fails. So, failure interaction between these three components is required to be analyzed using Markov and semi-Markov modeling depending upon the failure and repair mechanisms. Here the case of large domestic fan manufacturing industry in the state of Goa, India is taken up. As the industry does exports, the quality and reliability issues are quite vital.

LITERATURE REVIEW

The main disadvantage of the use of Markov processes is that they do not allow any other distribution for the sojourn times beyond the exponential one. But in most real world applications the life times and/or the repair times are not exponentially distributed. Malefaki, Limnios and Dersin compared the dependability measures obtained using semi-Markov with that of Markov processes. Further in their analysis they have considered the life time to follow exponential and repair time to follow general distributions and only numerical examples with varying parameters were studied.

Limmnios presented a general model for dependability measures for continuous and discrete time semi-Markov processes. Author proposed various theorems and Lemma to derive the dependability measures. The paper is limited to the theoretical and analytical treatment only.

Salfner and Malek have proposed that a

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proactive handling of faults requires that the risk of upcoming failures is continuously assessed. One of the promising approaches is online failure prediction, which means that the current state of the system is evaluated in order to predict the occurrence of failures in the near future. More specifically, it focuses on methods that use event-driven sources such as errors, uses Hidden Semi-Markov Models (HSMMs) for this purpose and demonstrates effectiveness based on field data of a commercial telecommunication system.

Cretu, Munteanu, Ludean, Vladean and Festila presented an analysis made on a single-phase induction motor, taking into consideration the most critical components that could lead to the failure of the motor. Furthermore, the auithors presented possible states of the motor and the importance of maintenance in the lifecycle of the motor. The auithors proposed that by having a well implemented maintenance policy, the life of the motor can be extended and unwanted defects can be avoided.

Bazzi Dominguez-Garcia and Krein presented a Markov reliability model of induction motor drives operating under field-oriented control. The model includes faults in the power electronics, machine, speed encoder, and current sensors. A complete Markov reliability model is developed to assess the mean time to failure of the system and other reliability factors. This analysis is shown to be simple and useful for assessing the reliability of motor drives.

Abhilash, Manjunatha, Ranjan and Tejamoorthy worked on electric motor drives that have seen widespread adoption in many applications. Due to considerable use of electric drives in industrial applications, reliability assessment of drive-motor systems both in design and operating phases is of considerable importance. The reliability factor of the motor drive system plays the vital role in process identity. Authors used Failure Mode and Effect Analysis (FMEA) approach to identify and list those component failures and combinations of component failures that result in an interruption of operation. The proposed technique is then applied to a practical drive-motor system and the results are presented.

RESEARCH METHODOLOGY

Modeling of the failure in single phase induction motor is done using Markov/Semi Markov models. System reliability is computed and compared with the actual system performance. Once the model is established we can evaluate various reliability improvement options available and improve system reliability and carry out cost benefit analysis.

To tackle the problem, first and foremost step is to plot the probability plots and get the distribution parameters. Since this problem is modeled by Markovian as well as Semi-Markovian, the probability plots of exponential and Weibull distribution were plotted to obtain the parameters which are presented in Table I.

Table I: Failure data analysis

Component	Distribution	Parameters
Start Capacitor	Exponential	$\lambda = 0.00820$
OC Switch	Exponential	$\lambda = 0.00857$
Auxiliary Winding	Exponential	$\lambda = 0.00037$
Start Capacitor	Weibull	$\theta = 132.49$, $\beta = 1.34$
OC Switch	Weibull	$\theta = 133.59$, $\beta = 1.42$
Auxiliary Winding	Weibull	$\theta = 2626.3$, $\beta = 1.60$

Markov Analysis

The single phase induction motor is modeled as a 3 component system in load sharing parallel having 2^3 i.e. 8 states. The reliability block diagram (RBD) is as shown in Fig.1.

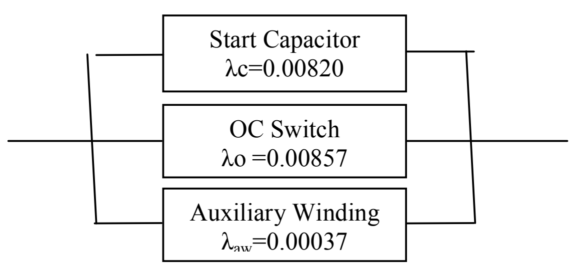

Figure 1: RBD of the motor system

λ_w=0.000370; $\lambda_2 = \lambda_c$ =0.00820; $\lambda_3 = \lambda_o$ =0.00857; $\lambda_4 = \lambda^*_{s/w}$ =2; $\lambda_5 = \lambda^*_{o/w}$ =2; $\lambda_6 = \lambda^*_{w/o}$ =2

$\lambda_7 = \lambda^*_{c/o} = 15$; $\lambda_8 = \lambda^*_{o/c} = 2$; $\lambda_9 = \lambda^*_{w/c} = 2$; $\lambda_{10} = \lambda^*_{o/c.w} = 2$; $\lambda_{11} = \lambda^*_{w/c.o} = 2$; $\lambda_{12} = \lambda^*_{c/w.o} = 15$

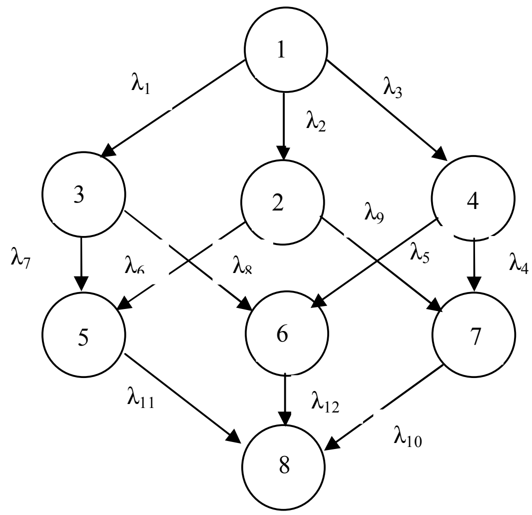

Figure 2: STD of the induction motor system

$$\begin{bmatrix} s+\lambda1+\lambda2+\lambda3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\lambda2 & s+\lambda9+\lambda8 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\lambda3 & 0 & s+\lambda7+\lambda6 & 0 & 0 & 0 & 0 & 0 \\ -\lambda1 & 0 & 0 & s+\lambda5+\lambda4 & 0 & 0 & 0 & 0 \\ 0 & -\lambda8 & -\lambda7 & 0 & s+\lambda11 & 0 & 0 & 0 \\ 0 & 0 & -\lambda6 & -\lambda5 & 0 & s+\lambda12 & 0 & 0 \\ 0 & -\lambda9 & 0 & -\lambda4 & 0 & 0 & s+\lambda10 & 0 \\ 0 & 0 & 0 & 0 & -\lambda11 & -\lambda12 & -\lambda10 & s \end{bmatrix} \begin{bmatrix} \bar{P}1(s) \\ \bar{P}2(s) \\ \bar{P}3(s) \\ \bar{P}4(s) \\ \bar{P}5(s) \\ \bar{P}6(s) \\ \bar{P}7(s) \\ \bar{P}8(s) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

Solving the above matrix equation

$$P1(t) = e^{-(\lambda1+\lambda2+\lambda3)} = 0.983 \tag{2}$$

$$P2(t) = \frac{\lambda2}{(-\lambda9-\lambda8)(\lambda1+\lambda2+\lambda3)}\left[e^{-(\lambda9+\lambda8)} - e^{-(\lambda1+\lambda2+\lambda3)}\right] = 0.00985 \tag{3}$$

$$P3(t) = \frac{\lambda3}{(-\lambda7-\lambda6)(\lambda1+\lambda2+\lambda3)}\left[e^{-(\lambda7+\lambda6)} - e^{-(\lambda1+\lambda2+\lambda3)}\right] = 0.00247 \tag{4}$$

$$P4(t) = \frac{\lambda1}{(-\lambda5-\lambda4)(\lambda1+\lambda2+\lambda3)}\left[e^{-(\lambda5+\lambda4)} - e^{-(\lambda1+\lambda2+\lambda3)}\right] = 0.000122 \tag{5}$$

$$\begin{aligned} P5(t) = {} & \\ & \left\{\left[\frac{\lambda *}{-\lambda9-\lambda8+\lambda11}(e^{-(\lambda9+\lambda8)} - e^{-(\lambda11)})\right] - \left[\frac{\lambda *}{-\lambda1-\lambda2-\lambda3+\lambda11}(e^{-(\lambda1+\lambda2+\lambda3)} - e^{-(\lambda11)})\right]\right\} * \\ & \left\{\left[\frac{\lambda \#}{-\lambda7-\lambda6+\lambda11}(e^{-(\lambda7+\lambda6)} - e^{-(\lambda11)})\right] - \left[\frac{\lambda \#}{-\lambda1-\lambda2-\lambda3+\lambda11}(e^{-(\lambda1+\lambda2+\lambda3)} - e^{-(\lambda11)})\right]\right\} \\ & = 0.000004048 \end{aligned} \tag{6}$$

Where,

$$\lambda * = \frac{\lambda 8 \lambda 2}{-\lambda 9 - \lambda 8 + \lambda 1 + \lambda 2 + \lambda 3} \quad (7)$$

And

$$\lambda \# = \frac{\lambda 7 \lambda 3}{-\lambda 7 - \lambda 6 + \lambda 1 + \lambda 2 + \lambda 3} \quad (8)$$

$$P6(t) = \left\{ \left[\frac{\lambda **}{-\lambda 7 - \lambda 8 + \lambda 12} (e^{-(\lambda 7 + \lambda 8)} - e^{-(\lambda 12)}) \right] - \left[\frac{\lambda **}{-\lambda 1 - \lambda 2 - \lambda 3 + \lambda 12} (e^{-(\lambda 1 + \lambda 2 + \lambda 3)} - e^{-(\lambda 12)}) \right] \right\} * \left\{ \left[\frac{\lambda \#\#}{-\lambda 5 - \lambda 4 + \lambda 12} (e^{-(\lambda 5 + \lambda 4)} - e^{-(\lambda 12)}) \right] - \left[\frac{\lambda \#\#}{-\lambda 1 - \lambda 2 - \lambda 3 + \lambda 12} (e^{-(\lambda 1 + \lambda 2 + \lambda 3)} - e^{-(\lambda 12)}) \right] \right\} = 6.16(10^{-10}) \quad (9)$$

Where,

$$\lambda ** = \frac{\lambda 6 \lambda 3}{(-\lambda 7 - \lambda 6 + \lambda 1 + \lambda 2 + \lambda 3)} \quad (10)$$

And

$$\lambda \#\# = \frac{\lambda 5 \lambda 1}{-\lambda 5 - \lambda 4 + \lambda 1 + \lambda 2 + \lambda 3} \quad (11)$$

$$P7(t) = \left\{ \left[\frac{\lambda ***}{-\lambda 9 - \lambda 8 + \lambda 10} (e^{-(\lambda 9 + \lambda 8)} - e^{-(\lambda 10)}) \right] - \left[\frac{\lambda ***}{-\lambda 1 - \lambda 2 - \lambda 3 + \lambda 10} (e^{-(\lambda 1 + \lambda 2 + \lambda 3)} - e^{-(\lambda 10)}) \right] \right\} * \left\{ \left[\frac{\lambda \#\#\#}{-\lambda 5 - \lambda 4 + \lambda 10} (e^{-(\lambda 5 + \lambda 4)} - e^{-(\lambda 10)}) \right] - \left[\frac{\lambda \#\#\#}{-\lambda 1 - \lambda 2 - \lambda 3 + \lambda 10} (e^{-(\lambda 1 + \lambda 2 + \lambda 3)} - e^{-(\lambda 10)}) \right] \right\} = 0.000002739 \quad (12)$$

Where,

$$\lambda *** = \frac{\lambda 9 \lambda 2}{-\lambda 9 - \lambda 8 + \lambda 1 + \lambda 2 + \lambda 3} \quad (13)$$

And

$$\lambda \#\#\# = \frac{\lambda 4 \lambda 1}{-\lambda 5 - \lambda 4 + \lambda 1 + \lambda 2 + \lambda 3} \quad (14)$$

Therefore system reliability,

R(t)=P1(t)+P2(t)+P3(t)+P4(t)+P5(t)+P6(t)+P7(t)= 0.9910 (15)

Reliability Assessment Using Software

Since the above calculation is very cumbersome to solve manually, software Isograph Reliability Workbench version 11.0 was used. From the above software analysis system reliability is found to be 0.991 and system reliability calculated manually was also 0.991. So we can conclude that reliability values given by the software and those calculated manually are equal. Therefore in the subsequent analysis this software is used to calculate system reliability.

RELIABILITY ASSESSMENT AND ENHACEMENT

Individual Component Reliability

Individual component reliability is calculated for a period of 1 year which is also the warranty period of the motor, so it is obvious that in order to reduce service cost we need to improve reliability of the component in this period. For calculating individual component reliability Exponential distribution is considered.

Table II: Failure data analysis

Component	Motor working (Hrs)	Component Working"1/λ" (Hrs)	Reliability Function	Reliability in %
Start Capacitor	2920	129.768	$e^{-\lambda c\ t}$	34.5
OC Switch	2920	129.768	$e^{-\lambda o\ t}$	32.88
Winding	2920	2920	$e^{-\lambda w\ t}$	33.94

From the above analysis it is found that OC Switch had the least individual reliability of 32.88%. So the cost related to improving OC Switch reliability and its subsequent system reliability improvement was analysed.

System Reliability Improvement

The switch was subjected to accelerated life test to simulate the actual working of the switch in the motor. In the accelerated life test the switch was kept on 15second on and 15 sec off cycle at the motor rated current and the point at which the switch sticks and fails was noted.

The switch with the single arm sustained 150000 cycles which in terms of hours of working is equal to 0.00416x150000 = 624 hours. Thus calculating reliability of OC switch using accelerated life test assuming exponential distribution we have λ=1/624=0.00160.

$$R\ (t) = e^{-\lambda oa * t} = 0.6881 \quad (16)$$

The switch with the double arm sustained 300000 cycles which in terms of hours of working is equal to 0.00416x300000=1248 hours. Thus calculating reliability of OC switch using accelerated life test assuming exponential distribution we have λ=1/1248=0.000801.

$$R\ (t) = e^{-\lambda o * t} = 0.8293 \quad (17)$$

Therefore the individual reliability is improved by 14% by introducing an additional contact arm. When the contact arm is assembled in the motor there is a reduction in reliability by 34% due to interaction between components. Therefore Failure rate will be λ=0.00260. Modeling the system with above failure rate, we have system reliability as 99.42% which is an improvement of system reliability by 0.32%.

Cost Benefit Analysis

1) Total number of motors produced with the above configuration= 80640 numbers
2) Total number of motors failed with the single arm OC Switch=80640x(1-0.983)=1370.88 is nearly equal to 1371 motors
3) Average cost of repair of these motors=Rs1096
4) Cost of service for the failed motors=1096x1371=Rs1502616
5) Cost associated with improving reliability:
   a. Cost of old switch +gear=Rs 65.38
   b. Cost of new switch+gear=Rs 205
   c. Difference in cost due to the above change=205-65.38=139.62
   d. Total cost increase of the motors due to addition of the double arm switch=139.62x80640 =Rs11258956.
6) cost of service for the failed motors after improving the reliability:
   a. total number of motors failed=80640x(1-0.989)=887.04 and the cost of service of these motors=Rs1096x887=Rs. 972152/-

From the above analysis we see that there is a service cost reduction of Rs 5.30 Lakh where as the investment required per year is Rs1.5 Crore.

RELIABILITY ASSESSMENT AND ANALYSIS USING SEMI MARKOV MODEL

Data analysis revealed that the failure phenomenon of the components follow Weibull distribution with β >1. Since conventional Markov model is appropriate only when the failure data follows exponential distribution, thus it becomes more appropriate that the systems reliability assessment can be done and analyzed using semi-Markov model. As the shape parameter of the Weibull distribution describing the failure phenomenon is greater than 1 method of stages can be employed to solve the problem.

Method of Stages For Start Capacitor

The failure of start capacitor follows Weibull distribution with parameters β=1.34 and θ =132.49. Since β>1 we can use method of stages in series to convert it to equivalent system with constant failure rate.

The first moment of Weibull distribution

$$M_1 = \theta \Gamma(1+\frac{1}{\beta}) = 121.63 \quad (18)$$

The second moment of Weibull distribution

$$M_2 = \theta^2 \Gamma(1+\frac{2}{\beta}) = 23170.75 \quad (19)$$

The constant failure rate ρ is given by

$$\rho = \lambda_1 = \frac{M_1^{\ 2}}{M_2 - M_1^{\ 2}} = 0.0145 \quad (20)$$

The number of stages α is given by

$\alpha = \rho * M_1 = 1.76 \sim 2$ (21)

Similarly the number of stages were found for OC switch and winding which are presented in Table III. Accordingly the STD was formulated as shown in Fig.2.

Table III: No. of stages for the motor system

Component	Weibull Parameters	Constant Failure Rate	Number of Stages
Start Capacitor	θ=132.49, β=1.34	0.0145	2
OC Switch	θ=133.59, β=1.42	0.0160	2
Winding	θ=2626.3, β=1.60	0.0010	3

Isograph System Reliability Workbench Version 11.0 was used to calculate system reliability and the system reliability was found to be 0.9999 which is higher than the reliability obtained by Markov model as 0.991. Using Isograph for semi-Markov with appropriate number of stages the reliability is obtained as 0.9863 which is closer to the actual field rejections of 2.2%.

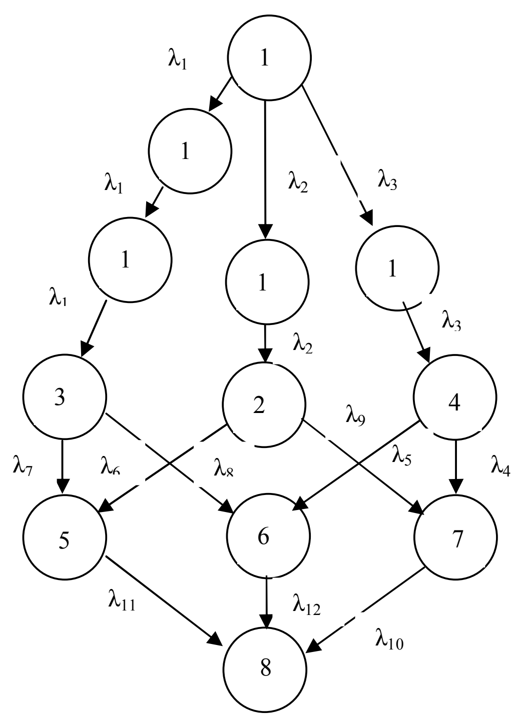

Figure 2: STD of the induction motor system with Weibull failure

System Reliability Improvement

The switch was subjected to accelerated life test to simulate the actual working of the switch in the motor. The switch with the single arm sustained 624 hours. Thus calculating reliability of OC switch using accelerated life test assuming Weibull distribution from historic data and mean = 624 hrs. giving θ as 687.22hrs.

$$R(t) = e^{-(t/\theta)^{\beta}} = 0.91 \quad (22)$$

The switch with the double arm sustained 1248 hours. Thus calculating reliability of OC switch using accelerated life test assuming Weibull distribution from historic data and mean=1248 hours giving θ as 1374.44 hrs.

$$R(t) = e^{-(t/\theta)^{\beta}} = 0.965 \quad (23)$$

Therefore the individual reliability is improved by 5.5% by introducing an additional contact arm. When the contact arm is assembled in the motor there is a reduction in reliability by 52.7% due to interaction between components.

Therefore when we simulate the system with double contact arm we will have to account for 52.7% reliability reduction when the switch is put in the system. Therefore R (t) =0.965x (1-0.527) which gives the characteristic life, θ = 153.88 hrs. The failure of OC Switch follows Weibull distribution with parameters β=1.42 and θ=153.88. Since β>1 method of stages is used. Replacing the failure rate of OC Switch with single arm with double arm failure rate and simulating the system for failures using Markovian model using Isograph Reliability workbench system reliability was calculated. It was seen that by replacing the system with a double arm OC Switch there is an improvement of reliability of the system from 98.63% to 98.71% which is an improvement of 0.08%.

RESULTS AND DISCUSSION

Cost Benefit Analysis

1) Total number of motors produced with the above configuration= 80640 numbers
2) Total number of motors failed with the single arm OC Switch=80640x(1-0.986)=1128.96 is nearly equal to 1129 motors
3) Average cost of repair of these motors=Rs1096
4) Cost of service for the failed motors=1096x1129=Rs1237384
5) Cost associated with improving reliability
   a. Cost of old switch +gear=Rs 65.38
   b. Cost of new switch+gear=Rs 205
   c. Difference in cost due to the above change=205-65.38=139.62
   d. Total cost increase in motors due to addition of the double arm switch=139.62x80640motors=Rs11258956.
6) Cost of service for the failed motors after improving the reliability
   a. Total number of motors failed=80640x(1-0.9871)=1040.256 is nearly equal to 1040 motors
   b. Cost of service of these motors=Rs1096x1040=Rs1139840

From the above analysis we see that there is a service cost reduction of Rs 97000 whereas the investment required per year is Rs1.5 Crore.

From the cost benefit analysis we see that the service cost reduction by improving the reliability of the system is less than the cost involved in improving the reliability of the component.

This problem was consulted with the senior management and a decision was made to go ahead with the change. The additional cost of reliability improvement will be absorbed by increase in the price of motor over a period of time. This reliability improvement will lead to increased customer satisfaction and in turn increase the customer base over a period of time.

Implementation Process

In order to implement the double arm contact switch, few changes in the assembly components had to be made, that included changes in the end cover, changes in the switch design and changes in the shaft.

Failure Analysis Post Implementation

Failure trend of each of the components i.e. the OC switch, the winding and the capacitor was plotted individually for the last two years and the analysis is presented below.

Winding Failure Analysis

From the box plot it was observed that the failure has reduced from a mean of 22000 PPM in 2011-12 to a mean of 14000 ppm in 2012-13. This shows a significant improvement in winding reliability with the changeover to the double arm contact switch instead of the single arm used earlier. Also from the box plot it was seen that the variation in the failure PPM in 2012-13 has reduced compared to the variation in failure PPM in 2011-12.

Start Capacitor Failure Analysis

From the Box plot of capacitor failure it was observed that there is no significant change in the failure PPM of the start capacitor. It has remained constant at around 2000 PPM as against 1900 PPM. The variation in failure PPM has slightly increased.

OC Switch and CF Gear Failure Analysis

From the box plot of OC Switch CF gear failure we see that there is an improvent in failure PPM. Failure

PPM has improved from around 4000 PPM to 3000 PPM and is a significant reduction of around 1000 PPM. Also there is reduction in variation in the failure PPM. This may be attributed to redundancy introduced in the OC Switch by having two parallel paths for current flow.

Old Switch

New Switch

Figure 3: Old and New Switch

CONCLUSION

The induction motor system of a large motor manufacturing unit in the state of Goa, India was modeled using Markov analysis and compared with software Isograph. Both the results are comparable. Reliability improvement options were modeled, evaluated and analyzed with cost benefit analysis. It was found that cost of investment is higher than the savings due to improved reliability.

The system was then modeled using Semi-Markov having Weibull Distribution with $\beta>1$ and system reliability was found out. The results of the model were justifying with the field experience. Reliability improvement options were evaluated and cost benefit analysis was done. It was found that cost of investment is higher than the savings due to improved reliability. This issue was consulted with the top level management and a decision was made to go ahead with the change. The additional cost of reliability improvement will be absorbed by increasing the price of motor over a period of time as this reliability improvement results in increased customer satisfaction.

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