Journal of Engineering and Applied Sciences 2 (5): 909-914, 2007

Large Squirrel Cage Induction Motor Reliability Modelling

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Abstract: In this study a simplified reliability model is developed on the basis of knowledge, from field data, of the dominating failure modes and mechanisms of large power squirrel cage induction motors operating at constant speed and fed from a conventional 3 phase sinusoidal supply voltage. Field data failures distribution indicates a dominance of failure modes pertaining to machine bearings and stator winding insulation. The motor system can be regarded as a complex combination of three fundamental parts: The stator, the rotor and the bearings which are , respectively electrical, electromechanical and mechanical in nature. On this basis, the motor system reliability block diagram is modelled in a series configuration comprising the above mentioned parts. The individual reliability functions developed for each part will yield together the overall motor system reliability.

Key words: Squirrel cage, induction, reliablity model, stator, rotor, modes

INTRODUCTION

The induction motor is the workhorse of industry. It accounts for more than 60% of the overall electrical energy consumption of any industrial nation. This pattern of consumption is also the case for Algeria. Hence its central importance in the national economy. Any operational failure will cause considerable economic losses therefore there is a pressing need to maximise the availability of this machine, hence its reliability.

Reliability is a very important performance parameter of induction machines but its modelling remains a very complex problem. However, in the light of field data, dominant failure modes of some motor system parts can be used to develop a simple but credible reliability model.

THE SQUIRREL CAGE INDUCTION MOTOR

The squirrel cage induction motor is the most common used type of induction motors in industry. It consists of 3 fundamental parts: A stationary part the stator fed from 3 phase supply setting a rotating magnetic field in the air gap responsible for torque production. The moving part, the rotor having electrically conducting bars shorted through end rings in the shape of a squirrel cage structure. Bearings at the rotor ends are a pivotal mechanical device that must dependably meet mechanical stress of the load as shown in Fig. 1 (Edward and Kirk, 2003).

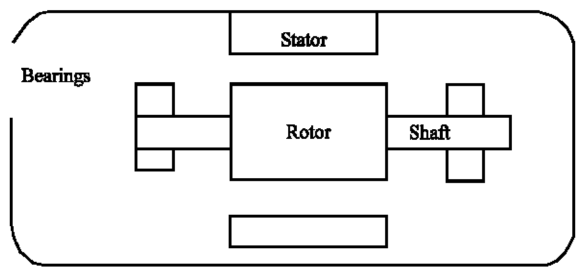

Fig. 1: AC induction motor

AC INDUCTION MOTOR FAILURE MECHANISMS

It has been shown that electric motor problems appear in two forms: Electric winding insulation problems and mechanical bearings and rotor difficulties as shown in the Table 1.

Electrical stator windings failure: It is shown in industrial surveys on machine reliability (Donnell, 1985) that the stator winding insulation is one of the most vulnerable components used in an AC electric machine.

The failure of stator winding can be divided into:

- Insulation degradation and breakdown.
- Open circuit failure of the winding wire.

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Insulation failure mechanism: The stator winding insulation is always subjected to the combined thermal, electrical mechanical and environmental stresses during the long-term operation (Table 2).

Thermal stress: Over time the insulation will deteriorate due to the normal thermal aging process; but the occurrence of premature failures, which are predominant, are a direct result of an over-current caused generally by an overload, an unbalance supply voltage and/or over-voltage.

Table 1: Motor failure statistics

Items	Source: Edward and Kirk, 2003	Donnell, 1985	IEEE-EPRI Curtis, 2002
	%		
Stator	37	30 to 40%	26-36%
Bearings	41	45 to 50	45-55
Rotor	10	8-12	
Other	12		

Table 2: Insulation failure causes distribution

Failure	Occurrence %
Overloads	30
Unbalance (Single-phasing)	14
Overvoltage	10
Contaminants	19
Ageing	18
Miscellaneous	9

Electrical stresses: Most of electrical failures are caused by a combination of over-voltage spikes and normal deterioration. This fast over-voltage can be caused by start-up switching, lightning, surges and VFD to propagate through the material, thus leading to a reduced time to breakdown.

Winding wire open circuit failure: This failure, which rarely occurs, is generally due to quality of wire as well as the level of electromechanical and environment stresses pressed on the winding wire. The open circuit failure may happen at the terminal connection of the motor.

The failure mechanisms sequence of the induction motor is summarized in the Fig. 2.

Mechanical Roller bearing failure mechanisms: According to reference (Donnell, 1985) bearing faults are a primary cause of failure of high power motor. Some

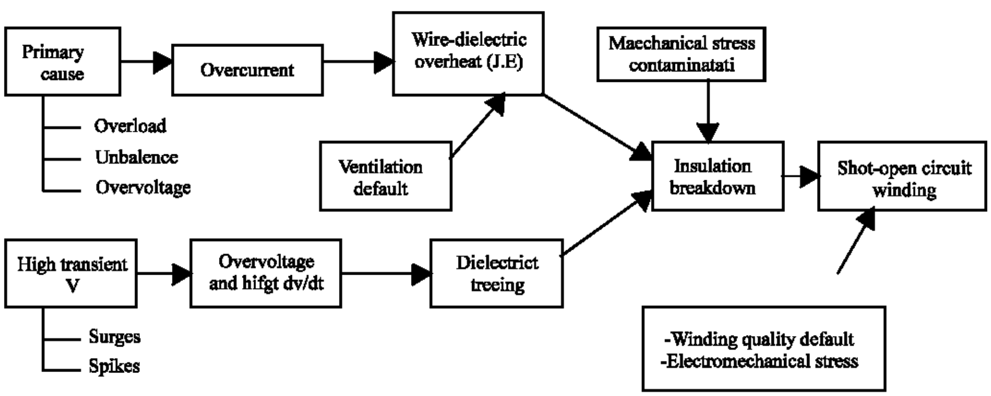

Fig. 2: Failure mechanisms sequence of the electrical stator windings

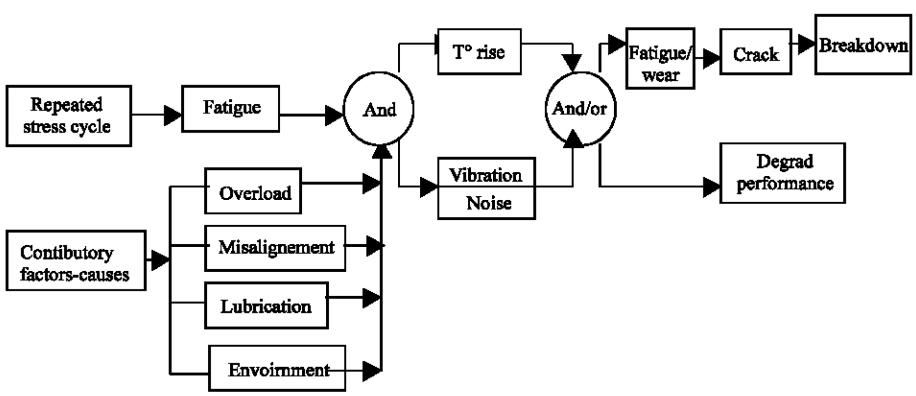

Fig. 3: Failure mechanisms sequence of the rolling bearings

Fig. 4: Failure mechanism sequence of the Rotor

Table 3: Bearing failure causes distribution (Edward and Kirk, 2003)

Failure causes	Occurrence %
Vendor probles, design quality	30.1
User-induced problems	37.4
Wear	28.5
Contaminant	4

Table 4: Detailed bearing failure causes distribution (Heinz and Fred, 1999)

Bearing Items failure causes	Distribution%
Contamination	45 to 55
lubrication	11 to 17
Improper assembly	11 to 13
Misalignement	10 to 13
Overloading	8 to10
Others	1 to 6

manufactures estimates that 95% of all bearing failures can be classified as premature. From statistical data and experience as shown in Table 3 and 4 of common bearing problems have been caused by normal deterioration combined with mechanical difficulties such coupling misalignment, overload and lubrication problems (under or over-greasing) as shown in the Fig. 3.

Despite numerous parameters having profound effect on the actual life of bearing, the L-10 bearing life is generally limited to material fatigue endurance only.

An example of current mechanical failure is a roller bearing that experiences distortion due to a loss of lubrication which is caused by excessive vibration.

Electro-mechanical rotor failure mechanism: The field data experience (Heinz and Fred, 1999) indicates that common problems of rotor-shaft assembly are caused by mechanical failures such as bars fracture, wear-out of end rings and excessive loading of the coupling shaft as shown in Fig. 4.

Associated shaft failures are generally attributed to combination of various stresses (mechanical, dynamic, thermal, environmental) which act upon the rotor assembly (Austin, 1999).

AC MOTOR RELIABILITY MODEL

The instantaneous failure rate experienced by motors are not constant but increases with time. The model is dictated by three failure modes: Stator winding insulation, bearing and rotor failures.

The motor system can be considered as a combined electrical, electromechanical and mechanical parts as shown in Fig. 5 where it may be assumed that motor fails when any of its parts fails such that its reliability bloc-diagram is modeled in series configuration which is expressed mathematically as follows:

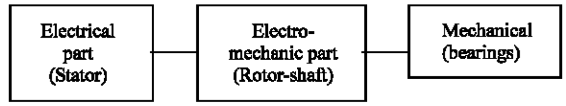

Fig. 5: Motor reliability bloc diagram

$$R_M = R_S.\ R_R.\ R_B \qquad (1)$$

Stator winding insulation reliability model: Since the insulation element can be represented by capacitance of high dielectric strength in parallel with a high value resistance its reliability is modeled in exponential form where the failure rate is constant.

This part failure rate is expressed as base failure rate times series of multiplicative stress factors related failure mechanisms given in section 3.1 with the following general form (MIL-HDBK, 1991):

$$\lambda p = \lambda_b.\ \pi_Q.\pi_E.\pi_T.\ \pi_S \qquad (2)$$

λb = Base failure rate
π_Q = Quality adjustment factor
π_E = Environment adjustment factor
π_T = Temperature adjustment factor
π_S = Electrical stress adjustment factor

Assuming that the MTBF of class F insulation is 80 000 h then the base failure rate is given by:

$$\lambda b = 1/MTBF = 1/80\ 000 = 12.5F/10^6\ h \qquad (3)$$

The temperature stress factor: The temperature acceleration factor is given by the Arrhenius model (MIL-HDBK, 1991):

$$\pi_T = \frac{\lambda_2}{\lambda_1} = \frac{MTBF_1}{MTBF_2} = e^{B_T\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (4)$$

Where constant B_T is determined using the half life rule for each 10° rise of the winding insulation temperature (Edward and Kirk, 2003) as:

$$B_T = \frac{\ln\left(\frac{1}{2}\right)}{\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} = -7.007\cdot 10^{+3} \qquad (5)$$

The activation energy of the insulation is deduced as follows:

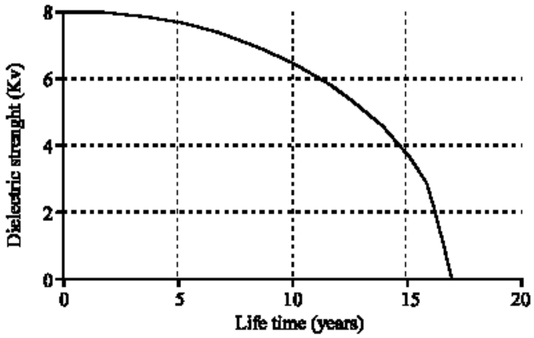

Fig. 6: Dielectric strength degradation

$$Ea = B_T. K (ev) \quad (6)$$

Where K: Boltzman constante (ev/K°)

The voltage acceleration stress factor πs: When a motor is new the dielectric strength of the insulation system is very high. On a typical 380 v motor the strength may be over 8 Kv to ground with turn-to-turn strength greater or equal to 4 Kv. The fast over-voltage stress will accelerate the degradation process of the insulation strength and this will continue to deteriorate to a level of breakdown (Curtis, 2002).

According to the degradation style of the dielectric strength whose voltage dependence is modelled with the following hyperbolic equation (Curtis, 2002):

$$V_s = 8 \cdot \sqrt{1-\left(t/17\right)^2} \quad (7)$$

Whose graphical representation is shown in the Fig. 6 as well as in Fig. 7.

While the time for given voltage is determined as to be:

$$t = 17 \cdot \sqrt{1-\left(V_s/8\right)^2} \quad (8)$$

The time to failure is evaluated as follows:

$$t_f = 16.6\text{-}t \quad (9)$$

Hence the degradation acceleration factor of the dielectric strength is evaluated as follows (Table 5).

$$\pi s = t_{f1}/_{tf2} \quad (10)$$

The quality and environment stress factors: Assuming that class F insulation of this induction motor has a best quality factor ($\pi_Q = 1$) and that the environment includes

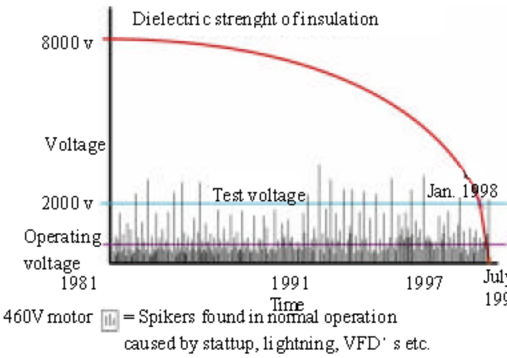

Fig. 7: Dielectric strenght insulation degradation (Curtis, 2002)

Table 5: Acceleration voltage stress factor

Parameters	Vs	t	T_f	$\pi s = t_f/_{tf2}$
Values	8	0	$T_{fmax} = 16.6$	1
	7	8.23	8.3699	1.983

Table 6: π-correction facrors

Parameters	λb	π_q	πe	πt	πs	λ_p
Values	12.5	1	2	1.4	1.983	69.405

Table 7: Time to failure of bearings

No. roller bearing	Life duration	Repartition function	N° roller bearing	Life duration	Repartition function
1	2000	10	6	9750	60
2	3520	20	7	11250	70
3	5035	30	8	13500	80
4	7050	40	9	17080	90
5	8510	50			

cement dust, dirt, corrosion and humidity is classed as GF according to MILHDBK (1991), whose accelerating stress factor is corresponding to $\pi_E = 2$.

The overall insulation failure rate: In the case of the following conditions such as 5° temperature rise and the dielectric strength of the insulation has reached 7Kv. The π-correction factors are given in the following Table 6:

The overall failure rate is calculated as:

$$\lambda p = \lambda_b.\ \pi_Q.\pi_E.\pi_T.\ \pi_S = 2.\ \lambda_b..\pi_T.\ \pi_S = 69.40F/10^6\ h(11)$$

Hence the reliability expression of the windings insulation is given as follows:

$$R_S(t) = e^{-69.405t} \quad (12)$$

This is represented graphically in the Fig. 8:

Bearing reliability model: The time to failure data of the rolling bearing of the considered driving motor in cement industry process are censored (Table 7).

Assuming that starting point Y = 0, the Weibull shape and scale parameters are determined using Allan Plait graphical sheet (Lyonnet, 1988) as to be:

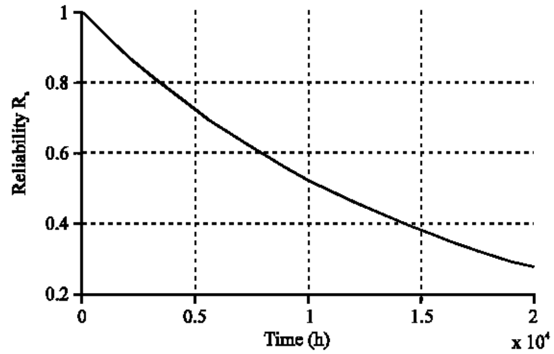

Fig. 8: Reliability curve of the winding insulation

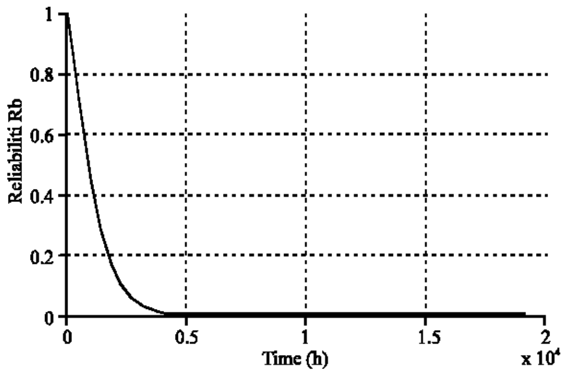

Fig. 9: Reliability model of rolling bearing

Table 8: Life durations of the rortor-shaft

No. rotor	Life duration	No. rotor	Life duration
1	95000	5	11150
2	11500	6	12800
3	13000	7	14100
4	12560	8	10050

-β = 1.35 that is characterising fatigue and wear-out failure mode;

-η = 10000 h

And hence the reliability will be expressed as follows:

$$R_b(t) = e^{-\left(\frac{t}{10000}\right)^{1.35}} \quad (13)$$

This is represented graphically in Fig. 9.

The high proportion of bearing premature failure are due to high dynamic inertia of this high power low speed induction motor., user induced problems and an aggressive dusty environment (Heins and Fred, 1999).

Electro-mechanical rotor reliability model: The rotor of this AC induction motor used has censored the following life durations (Table 8).

This rotor-shaft presents fatigue wear-out that is normal distribution with mean m = 11833 h found to be operating hours and variance σ = 1565.9:

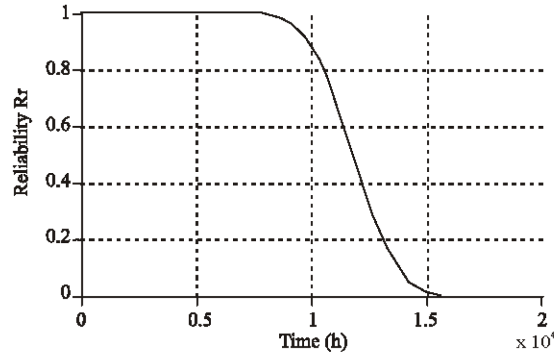

Fig. 10: Reliability evolution of the rotor

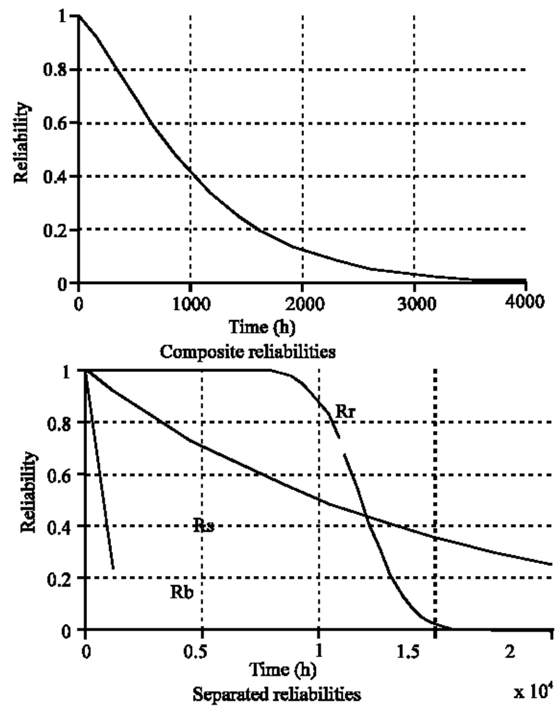

Fig. 11: The overall reliability of the electric AC motor

$$Rr(t) = 1 - \int_0^t \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(t-m)^2}{2\sigma^2}\right) \cdot dt \quad (14)$$

This is represented graphically in (Fig. 10).

As long as they are kept within the intended design and application limits, rotor-shaft failures should not occur during the expected life of the motor.

Overall reliability of the induction motor: According to equation the overall reliability of the induction motor is obtained:

$$R_M(t) = e^{-86.84 \cdot t} \cdot e^{-\left(\frac{t}{10000}\right)^{1.35}} \cdot \left(1 - \int_0^t \frac{1}{(1565.9)\sqrt{2\pi}} \exp\left(\frac{-(t-11833)^2}{2 \cdot (1565.9)^2}\right) \cdot dt\right) \quad (15)$$

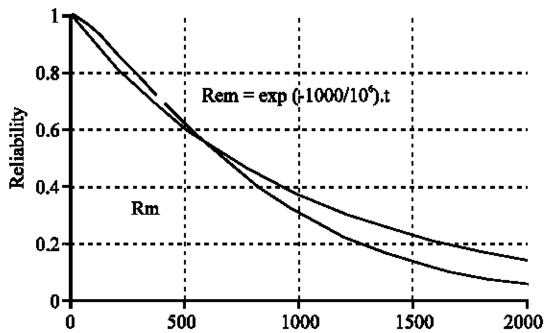

Fig. 12: Graphical comparison of the overall reliability of the induction motor with an exponential form reliability of constant failure rate (˜1 F/1000h)

The corresponding graphical representation is given in Fig. 11 and 12.

CONCLUSION

In this study, it is shown that the Weibull Law is well suited to the mechanical roller bearings failures distribution while the insulation degradation (or reliability), because its electro-chemical nature, is adequately represented by an exponential form function. The rotor-shaft assembly failure distribution follows the normal law because of the dominant fatigue phenomenon. The obtained overall reliability of the induction motor essentially follows an exponential form function for a limited time interval but with a relatively much higher constant failure rate, than that of the winding insulation as shown in Fig. 12 because of the precipitating effect of bearings reliability slope. It is hence concluded that the remaining life of large motor is decided by the bearings life to a great extent and the life stator insulation system.

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