Medium Induction Motor Winding Insulation Protection System Reliability Evaluation and Improvement Using Predictive Analysis

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- Abstract : The paper presents a quantitative reliability evaluation of a widely used protection system for medium power cage induction motors. This evaluation effort is based on a predictive analysis using ETA and FMECA in conjunction with field data regarding dominating failure mechanisms and causes of windings insulation breakdown. Dominant failure modes and failure mechanisms are analysed and then initiating causes of motor failures and their weighted contribution factors determined. An Event Tree Analysis is then developed for predicting the probability of the protection system outcomes. An FMECA is developed in order to provide the guidelines for actions in the framework of reliability improvement and a preventive maintenance program with particular attention given to environmental factors such as found in a cement plant.
Key words: Protection, reliability, failure mechanisms, even tree, FMECA, improvement.

1 Introduction

The induction motor is the workhorse of industry. Any operational failure, due to several impressed stresses, will cause considerable economic losses therefore there is a pressing need to maximise the protection and the availability of these ac machines.
However, in the light of field data, dominant failure modes and failure mechanisms of some motor system part, **t**he initiating causes of motor failure and their weighted contribution factors are determined. An Event Tree and FMECA Analyses are then developed for reliability evaluation and improvement of this protection system.

2 Induction motor stator winding failure mechanisms

Industrial surveys on machine reliability shows [3] 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 hence breakdown.
- Open circuit failure in the windings.

2.1 Insulation Failure Mechanisms (IFM)

The stator winding insulation is always subjected to the combined thermal, electrical mechanical and environmental stresses during the long-term operation [7].

2.1.1 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, a supply voltage unbalance and/ or over-voltage.

2.1.2 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 [5].

2. 2 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

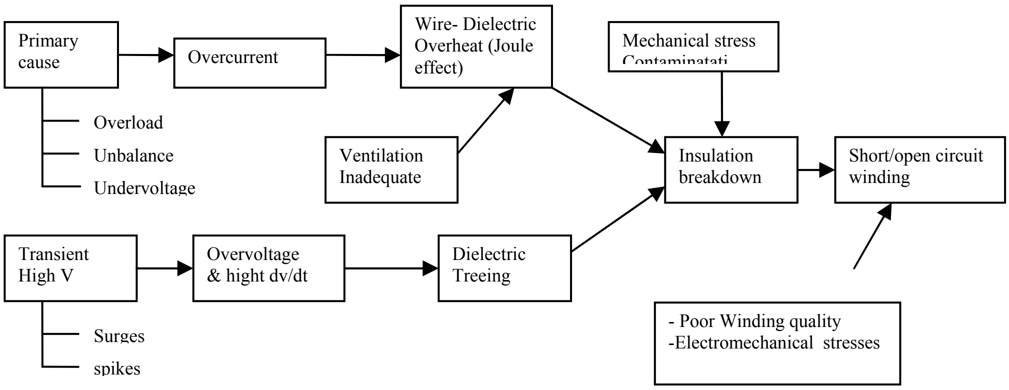

Fig 1 Failure mechanisms sequence of the electrical stator windings

According to the statistical data given in the table A1 of Appendix, the family of failure causes of the motor insulation breakdown are predominant [3] and among them the overload presents the highest percentage of causes followed by unbalance and overvoltages.

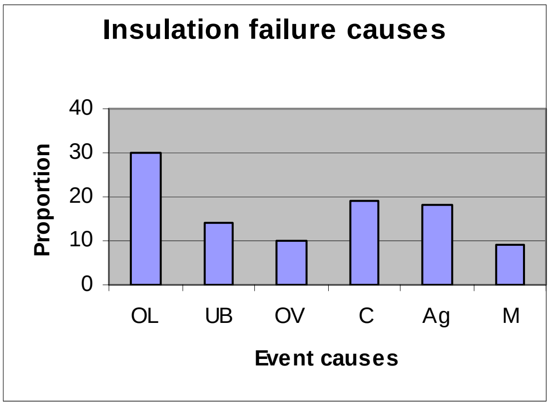

Fig.2 Insulation failure initiating causes distribution

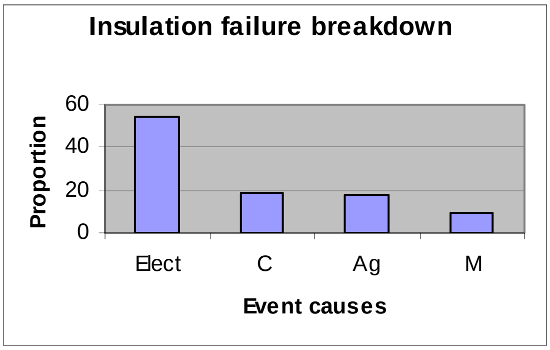

Fig.3 Insulation failure modes distribution

The overload is mostly caused by mechanical problems due to excess loads or jams in the driven machine which forces the motor to supply higher torque, draw more current and hence overheat.

3 Failure probability quantification

Assuming that the failure rate of the motor is constant for a given time interval 10^{-5} h and is evaluated as 10 F/10^{-6} and that 40% of the motor failure are due to stator insulation breakdown then the probability of failure of the undesirable stator insulation breakdown is evaluated [1] as:

$$F = 1 - R(t) = 1 - e^{-4.10^{-6}.t} \qquad (1)$$

According to failure causes distribution, the contribution to the insulation breakdown of each initiating event (overload, unbalance..) is expressed:

$$Fc = \alpha \,.\, F \qquad (2)$$

The importance factors and the weighted failure probabilities are given in table 1 :

Initiating Event	**Contribution factor α (%)**	**$P_{Failure}$ Fc**	
OL (Overload)	50	P_{OL}	$2*10^{-2}$
UB (single phasing)	20	P_{UB}	$8*10^{-3}$
OV(Overvoltage)	10	P_{OV}	$4*10^{-3}$
OH(ambia.overheat)	10	P_{OH}	$4*10^{-3}$
Others	10		$4*10^{-3}$

Table1 Insulation failures importance factors

4 Protection system description

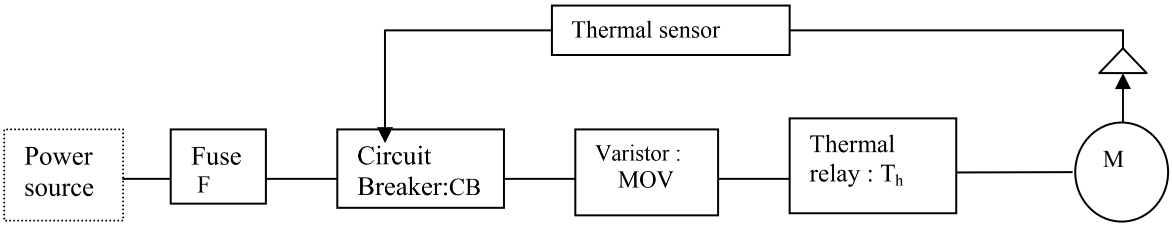

Fig.4 Protection system

Based on the previous hierarchization of the initiating failure causes and IFM, the priority protection is provided fist against overload followed by the unbalance (single phasing) and the over-voltages. The parameters to be controlled are mainly the over-current, the overheat and the over-voltage.
While satisfying conditions such as discrimination, selectivity and reliability, the credible optimized induction motor protection system consists fundamentally of thermal relay, varistor, circuit breaker, fuse and thermal sensor circuit as shown in Fig.4.
With the principle function of current and temperature detection–isolation, the thermal relay provides an overload protection. The metal oxide varistor (MOV) is used to clamp any slow or fast over voltage from the power supply source. The circuit breaker is used to protect the motor from short-circuit condition.. The thermal sensor embedded on the stator winding is used to protect from high ambient temperature as well as the overload fault condition. The fuse opens its current responsive element in the case of an overcurrent or short circuit condition [4].

The back up protection is provided in the case of the overload and single phasing. If the thermal relays fails to open , the thermal sensor circuit or the fuse is activated as shown in the table A7 of Appendix.

5 Event Tree Analysis (ETA)

An event tree starts with specific initiating cause such as an overload, unbalance or over-voltage as identified in the previous IFM and then follows the possible progression of the incident according to the success or failure of the protection devices. This conducts to the elaboration of the sequence of events that leads to the insulation protection or severe motor failure and breakdown .
Each of the identified paths is evaluated [1]:
- qualitatively by simplifying and eliminating impossible branches
- quantitatively by attaching the probability to each event on the tree with the assumption that the failures are independent.

The reduced and quantified ETA for each initiating event are obtained as follows:

Initiating cause	Overcurent therrmal Relay	T° sensor	Fuse	Consequences	P
Overload P_{OL}=.02	S P_{TH} =.979			ITP	P_{OL} P_T =.0195
	F (1- P_{TH}) .021	S P_{TS}=.962		ITP	P_{OL} (1- P_{TH}) P_{TS} = .04*10-2
		F (1- P_{TS})=.037	S P_F= .999	I B &SC-P	P_{OL} (1- P_{TH}) P_F= .1552*10-4
			F (1- P_F=.001	Motor Deterio+Fire	P_{OL} (1- P_{TH})(1-P_F)=.1554*10-7

Fig 5 ETA for the overload initiating event

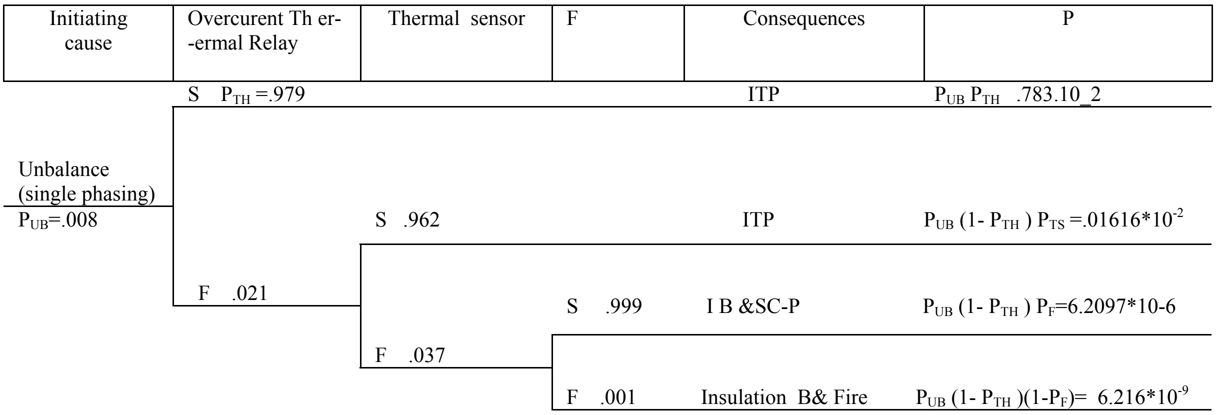

Fig 6 ETA for an unbalance (single phasing) initiating event

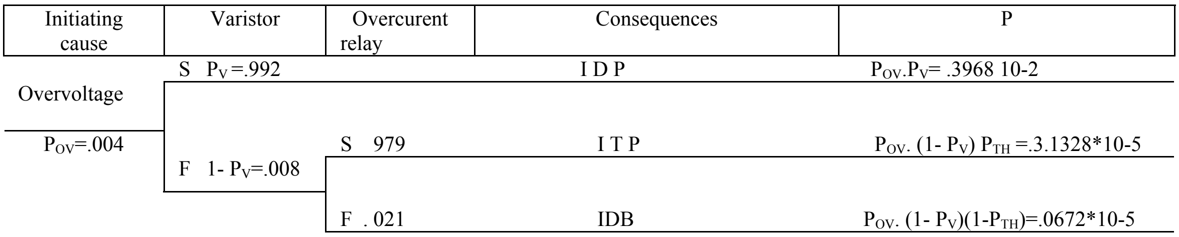

Fig 7 The reduced ETA for initiating over-voltage event

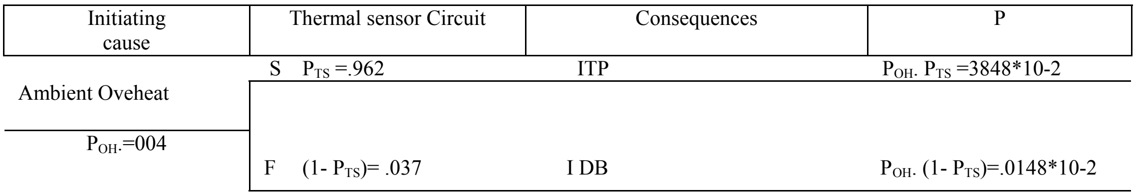

Fig..8 The reduced ETA for initiating ambient overheating event

The obtained results indicated in the column 3 of table A6 show that the overall probability of insulation protection outcomes P_{IP} is much greater than that of the insulation breakdown outcome P_{IB} by of more than 200 but further improvement is possible.

5 Protection system improvement

The improvement on the quality of the protection system will be based on an improved reliability and a continuous preventive maintenance of the protective devices to increase the probability of the insulation protection outcomes.

5.1 Reliability improvement

Improved reliability is obtained by the use of more reliable individual protective elements as well as by the redundancy (backup).This will increase the probability of success outcomes against dominant initiating events.

5.1.1 Better quality factor

The influence of quality factor is shown according to part stress method [6] where the failure rate is given as:

$$\lambda p = \lambda B \ \pi Q . \pi E \qquad (3)$$

λB = base failure rate
πQ = quality adjustment factor
πE = environment adjustment factor

By using better quality of the critical protective devices as shown in table A4 of Appendix , the obtained values of the probability of the consequence of insulation protection has increased while the probability of the insulation breakdown has decreased by the ratio of more than 2 as shown in the table A6 of Appendix .

5.1.2 Redundancy

In this case reliability can be increased by applying an active redundancy at thermal sensor circuit. A similar output circuit is added in parallel so that one can fail without causing system failure of the protection in the case of an ambient overheat or overload. The new increased reliability of the circuit is expressed as:

$$R = 2R - R^2 \qquad (4)$$

A substantial improvement is obtained :

$$R_{Improved} (= .998) > R_{Before}(= .962) \qquad (5)$$

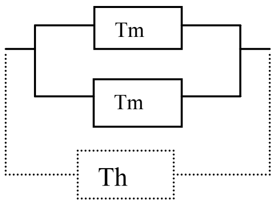

Fig.9 Redundancy at thermal sensor circuit

This behaves as improved back up for thermal relay in the case of an overload condition.

5.2 Preventive maintenance on the protection system

To preserve an inherent reliability and successful function of this protection system a periodic preventive maintenance of its constitutive devices and their connection is required. Preventive actions and particularly environment protection against dust, temperature, vibrations and contamination are taken in the light of FMECA shown in the Table 3 of Appendix so that Π_E factor is reduced and hence more than 20% reduction of the failure rate of the motor has been obtained [8].

This will prevent from any failure or degradation of the critical protective device and their connection leading to an undesirable event such as single phasing and loss of protection .

6 Conclusion

The calculation results of the evaluation of the protection system reliability using Failure Mechanisms and Event Tree Analyses indicate as expected shown that the probability of ensuring successful insulation protection is much greater than a failed insulation protection leading to insulation breakdown by a ratio of more than 200.

Despite the inherent high probability of successful ensured insulation protection, there is still a margin of improvement of system protection reliability. Through the selection of better quality protective devices, together with the use of redundancy where needed and a preventive maintenance on the protection system proper in order to reduce the negative impacts of an aggressive environment such as that of a cement plant, a drastic reduction of 60% in the probability of failed protection can be achieved.

The protection system and the motor reliability and availability can therefore be dramatically improved in a cost effective manner.

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- Appendix

Items	**[8]**	**[3]**	**IEEE-EPRI [5]**
	%		
Stator windins Ins	37	30% to 40%	26-36%
Bearings	41	45 to 50	45 – 55
Rotor	10	8-12	
Others	12		

Table A1 Motor Failures statistics

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

Table A2 Insulation failure causes distribution

Component	**λb F/10-6**	**πE (GF)**		**πQ**		π		π	**λp**		**R**		**F**	
		B	A	B	A				B	A	B	A	B	**A**
Over-I-Relay	.25	1	1	3	**1**			πL =2.72	2.04	.68	.979	**.993**	.021	.007
Ckt Breaker	.5	2	2	1	1	πC=3		πU=1	3	3	.970	.970	.029	.029
Fuse	.010	2	2	1	1				.02	.02	.999	.999	.001	.001
Varistor	.023	6	6	2.4(Jan	**1** Jantx	2.2	1.2		.728	.165	.992	**.998**	.001	.002
Thermal-sensor	.53	3	**3**	2.4	**1**				3.87	1.59	.962	**.984**	.037	.016

Table failure rate and failure probability of protective devices A3 (B: before , A: After improvement)

Initiating cause	**Consequences**	**Probability**		Ratio: A/B
		Before	After improv	
OL	Insulation Thermal protection : ITP	$1.99155*10^{-2}$	$1.9998*10^{-2}$	
UB	ITP	$.79976*10^{-2}$	$.80826*10^{-2}$	
OV	ITP	$.0031328*10^{-2}$	$.07944*10^{-4}$	
OH	ITP	$.3848*10^{-2}$	$.3936*10^{-2}$	
OL+UB+OH	*ITP* $P_{itp}=\Sigma P_{itpi}$	$3.1792428*10^{-2}$	**3.20245***10^{-2}	
OV	Insulation Dielectric protection IDP	P_{dp} =.3968 10^{-2}	.3992. 10^{-2}	
OL+Ub+OV+OH	Overall Insulation protection	P_{IP} =3.57604*10^{-2}	**3.6016539**10^{-2}	
	Insulation breakdown	$\mathbf{P_{IB}}$ **=1.48693*10^{-4}**	**.640873*10^{-4}**	**0.43**

Table A4 Probability of occurrence of the consequences

N°	**Item**	**Function**	**Failure mode**	**λ F/10-6 h**	**Cause**	**Effect**	**C**	**Preventive maintenance**
	Thermal Relay	Oveload Protection	-Contacts Fail Shorted -Coil Fails Open -heater failure	2.04	-Contacts Welded -Coil OC -Incorrect setting of tripping I	- Loss of thermal protection -Overheat	A	-removing weld -Testability
	Circuit breaker	Protection against short circuit	-Contacts Fail Shorted (stick occasionnally) -Contacts Fail Open -Fails to active	3	-Contacts Welded corroded & Dirty -Mechanical Failure binding -Incorrect setting of tripping I	Loss of short circuit protection, -severe breakdown -overload	A	-Cleaner vaporizer contacts - dust removing - trip setting
	Fuses	Protection sc overcurrent	-SC -OC	.02	Overcurrent -Inaquate rating	-shutdown -Unbalance		-replacement -adequate rating
	Varistor	Protection against fast overvoltage, surges, spikes	- SC - OC	.0411	Excessive pics of voltage	-CB activat -Loss of dielectic protection	D	-replacement -adequate rating - G.rounding-filters
	Thermist ance -ckt	Stator ambient T° monitor	OC	3.87	-Overheat dirty dusty and corrosive Environment	-Overheat -reduced aging	A	-cleaning -control ventilation
	Terminal s- lines Transmis sion	Electrical conduction	Contacts Fails OC Open	2.5	-Loose scew -Poor contact -Corrosion	Unbalance (phase loss)	B	Periodic Check contact ans Tire the knut

Fig A5 FMECA table of Protection system (C:criticality)