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Reliability Assessment and Improvement of Large Power Induction Motor Winding Insulation Protection System Using Predictive Analysis

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Abstract: The paper presents a reliability assessment of a widely used protection system of large power squirrel cage induction motors. In conjunction with published field induction motors Failure data this assessment effort is based on a integrated predictive analysis using three methods: (1) a Fault Tree Analysis (FTA) that allows to identify and then quantify the initiating failure cause weighting factors; (2) an Event Tree Analysis (ETA) that allows to predict the protection system probability outcomes following an external disturbance and (3) a Failure Mode Effect and Criticality Analysis (FMECA) that will help set the stage for developing a preventive maintenance program fit to keep up the induction motor protection system reliability at the required level with particular attention given to aggressive environmental factors such as found in cement plants.

Key words: FTA, ETA, FMECA, Induction motors , Protection, Reliability , Failure Modes.

1 Introduction

The induced draft fan high power induction motor, that draws hot gas off the rotary kiln, is a central piece of cement industry process. Despite its robustness and arguably high reliability it has its physical limitations which, if exceeded, will result in premature failure. Any operational failure will cause plant shut down and hence considerable economic losses. There is therefore a great need to improve the motor availability through improving its protection system.

According to published failure rates, bearings and winding insulation failures are by far the most dominant failures of large induction motors [1-2-3] together, they represent about 80% of the total number of motor failures.

Failures of bearings can be detected during operation at an early stage from vibration measurements; insulation failures are comparatively faster developing failures for which adequate monitoring approaches have not yet fully matured [4] and [6], calling for attention to be focused on this latter aspect.

In the present work, dominant failure modes and failure mechanisms of motor insulation parts, the initiating causes of

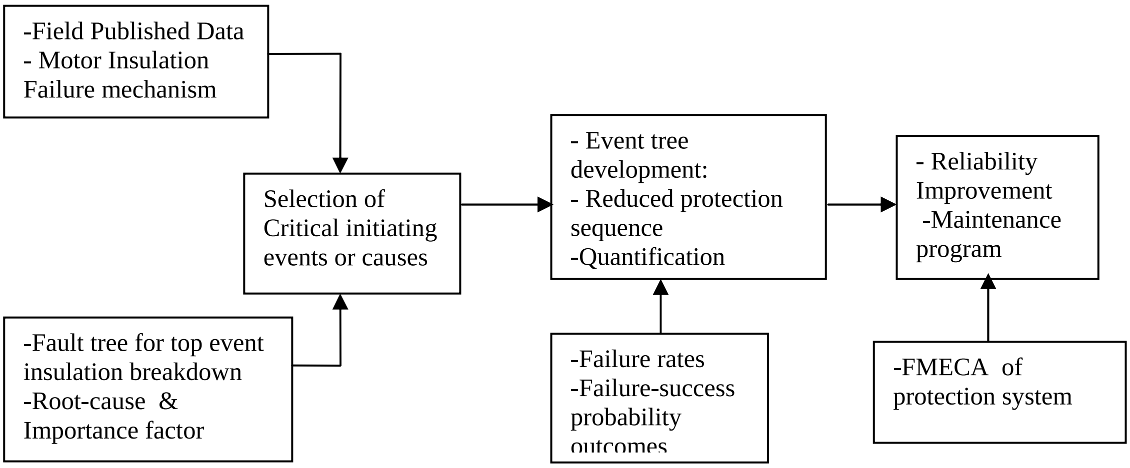


Fig1 Reliability assessment approach of large induction motor insulation protection system

failure and their weighted contribution factors are first determined making use of published reliability data. FTA, ETA and FMECA analyses are then developed for the assessment of the motor electrical protection system reliability followed by a given number of measures to be taken in the framework of a preventive maintenance program.

The followed fundamental approach is depicted in the block diagram shown in Fig.1

2 Induction motor stator insulation failure mechanisms

The electrical insulation material is one of the most critical and vulnerable components for operation of large AC electric machines. There has been a substantial effort in identifying the causes of stator insulation degradation and failure [2].

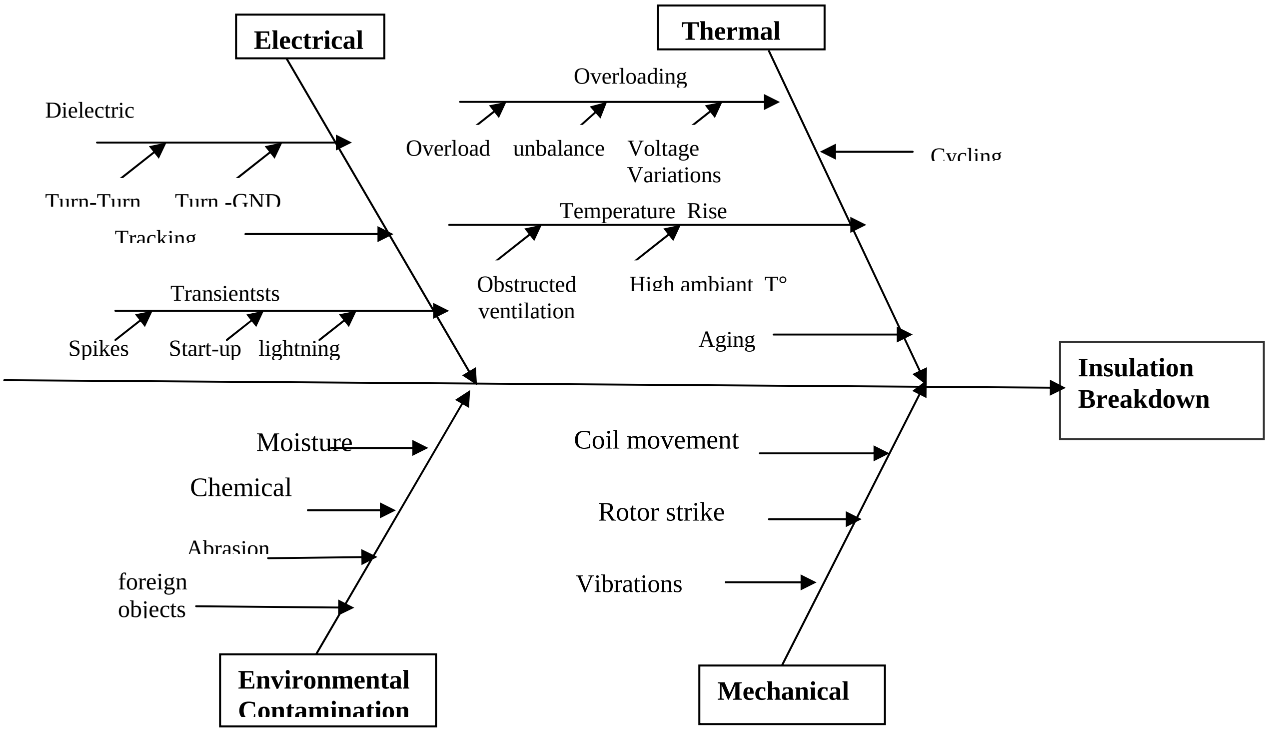


Fig.2 Insulation failure mechanism

2.1 Insulation Failure Mechanisms (IFM)

The stator winding insulation is always subjected to the combined thermal, electrical, mechanical and environmental stresses during long-term machine operation [2].

2.1.1 Thermal stress

Over time, the insulation material will deteriorate due to the normal thermal aging process; but the occurrence of premature failures, which are predominant, are a direct result of an overheat due to an over-current caused generally by an overload, a voltage unbalance and/or voltage variations [2] and [3]. High ambient temperature and obstructed ventilation are also other causes of thermal stresses which can lead to the delamination or cracking of the insulation [2]

which can lead to the delamination or cracking of the insulation [2] .

The temperature stress acceleration factor is given by the Arrhenius model [6]:

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

Where λ_1 and λ_2 are failure rates at respectively temperatures T_1 and T_2 and B_T is constant determined using the half life rule for each 10° rise of the winding insulation temperature [8].

2.1.2 Electrical stresses

The repetitive turn to turn or turn to ground electrical stresses and tracking may lead to dielectric degradation [2].

According to the degradation style of the dielectric strength whose voltage time dependence is modelled with the following hyperbolic equation [5]:

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

Where V_s = the dielectric strenght voltage
t = time

Most of electrical failures are caused by a combination of over-voltage and normal developing deterioration through its gradual loss of dielectric strength. The fast over-voltages or transients can be caused by start-up switching, lightning, surges that propagate through the insulation material, thus leading to a premature breakdown [5].

2.1.3 Environment and mechanical stresses

The contamination and moisture can contribute to faster chemical degradation of the insulation material that is organic in nature while mechanical vibrations or coils movements stresses may cause abrasion [2].

2.2 Statistical distribution of insulation failure causes

The surveys published in [1-2] show that 30-40% of AC machine failures are initiated from problems in the stator insulation; and according to the statistical failures data given in the table A1 of Appendix it is shown that among the failure causes of the motor insulation breakdown the overload and the unbalance are predominant [1] followed by over-voltages as shown in Fig 3 .

Overload and unbalance together can reach 50 % of the overall insulation failure causes.

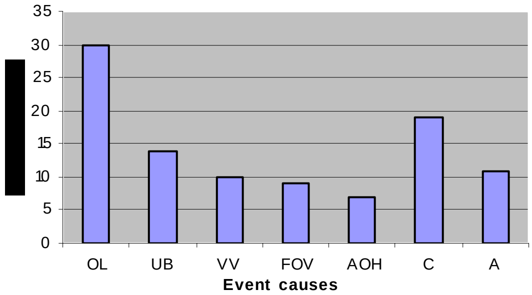


FIg.3 Insulation failure causes distribution

- *Overload:*

It is mostly caused by mechanical problems due to excess loads or jams in the driven machine which forces the motor to develop higher torque, draw more current and hence overheat [3].

-*Supply Unbalance:*

Supply voltage unbalance caused by unbalanced loads and /or asymmetry in 3 phase impedance is the phase voltage deviation from the average of all 3 phase voltages, single phasing representing the worst case. Even a small voltage unbalance will result in comparatively much larger currents that will cause very substantial increase in the winding temperature and losses.

3 Failure probability quantification

Assuming that the failure rate of the motor is constant for a given time interval 10^4 hours and is estimated as 10 F/10^6 hours and that 40% of the motor failures are due to stator insulation breakdown then the probability of occurrence of the undesirable stator insulation breakdown is given by [7] :

$$F = 1 - R(t) = 1 - e^{-4.10^{-6}.t} \qquad (3)$$

According to failure causes distribution, the probability of contribution to insulation breakdown of each initiating event (overload, voltage imbalance..) is expressed as follows:

$$Fc = \alpha \,.\, F \qquad (4)$$

Where α is the importance factor expressed in % . The weighted failure probability values of *Fc* are given in table 1:

Table1 Insulation failures contribution probabilities

Initiating Electrical causes	**α** (%)	**Fc**	
OL (Overload)	30	P_{OL}	$1.14*10^{-2}$
UB (unbalance)	14	P_{UB}	$5.32*10^{-3}$
(VV)Voltage Variations	9	P_{VV}	$3.8*10^{-3}$
FOV(Fast Overvoltage)	10	P_{OV}	$3.42*10^{-3}$
OH(ambian.overheat)	7	P_{OH}	$2.66*10^{-3}$

4 Fault Tree Analysis (FTA) of stator failure

A Fault Tree is constructed to determine all possible causes that can lead to the undesirable top event which is motor insulation breakdown as illustrated in Fig.3. The causes thus identified by the FTA will constitute the initiating events for developing an Event Tree Analysis that will be described subsequently.

The obtained weighted importance factor of the cause will provide the priority protection parameter .

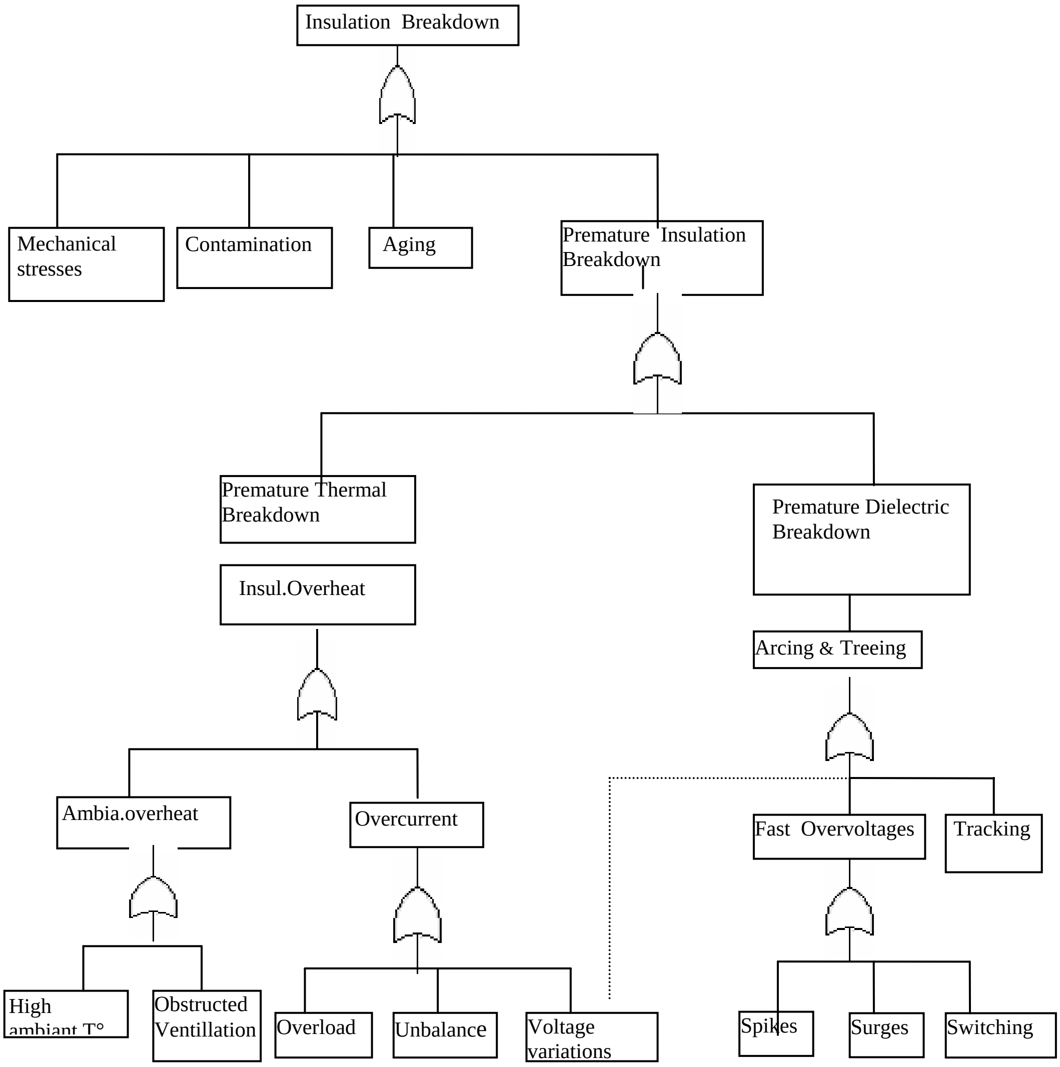


Fig 4 Fault Tree for stator insulation breakdown

5 Protection system description

Based on the previous hierarchization of the initiating failure causes and IFM, protection priority is provided first against overloads then unbalance , voltage variations, overheating and fast over-voltages in this order . The parameters to be controlled are mainly the current, voltage and temperature.

A large induction motor protection system must be able to meet discrimination, selectivity and reliability requirements. It basically consists of current and potential transformers, thermal sensors, an associated circuit breaker, fuses and varistors (or surge arresters) [8] as shown in Fig.5.

With the principle of detection–isolation function, abnormality in current, voltage or temperature parameter is detected to trip a common circuit breaker /contactor [9].

The coordination between different protective devices is based on the choice of the time delay and setting of trip values to provide an efficient backup protection sequence for each fault condition as indicated in table 2. From a point of view reliability, the back up protection is seen as a passive or stand-by redundancy. It is a well established protection practice against critical events such as overload and supply unbalance .

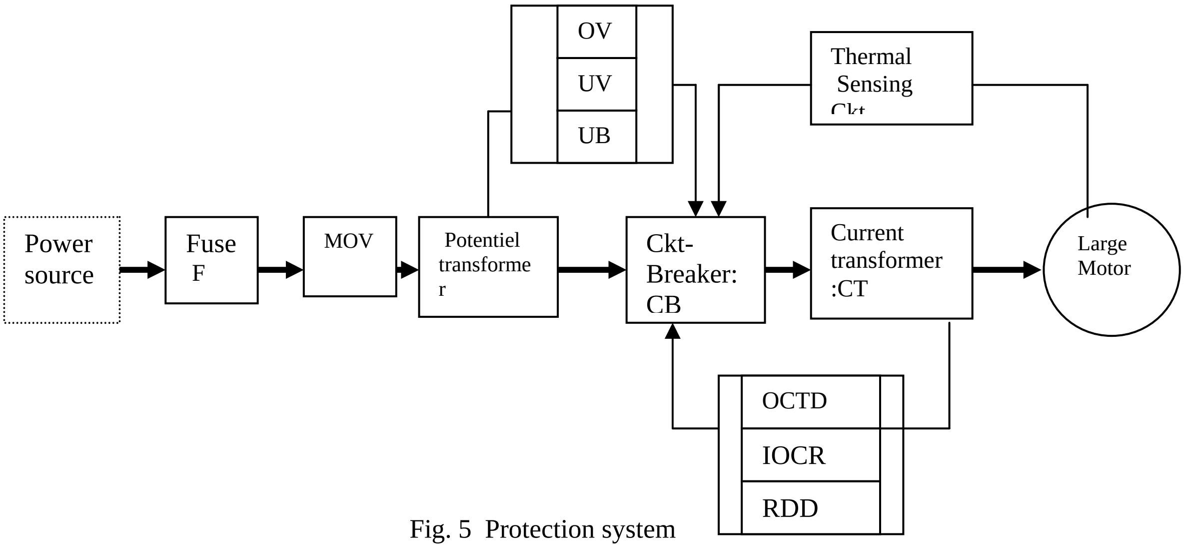
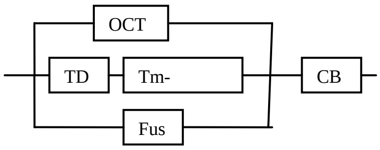
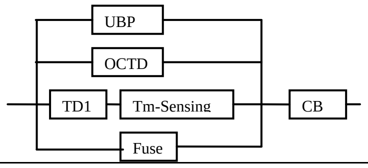
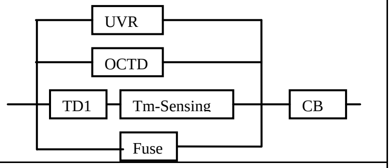


Fig. 5 Protection system

Table 2 Faults and protection sequences

Fault	**Protective device**	**Protection Sequence** (with Possible backup and passive redundancy reliability diagram)
1-Overload condition	OCTD-CB Overcurrent relay with Time Delay	OCTD-CB➔Tm-CB➔F 
2-Unbalance (single phasing) (Negative sequence)	-UBP-CB (PT) Unbalance Protection relay	UBP➔OCTD-CB➔Tm-CB➔F 
-Voltage variation : -Under voltage -Overvoltage	-UVR-CB - OVR-CB Under or over voltage protection relay	UVR➔OCTD-CB➔Tm-CB➔F OVR➔MOV 
Fault	**Protective device**	**Protection Sequence**
5-Restricted ventilation - High ambient temperature	Tm-CB Thermal sensing cicuit Tab-CB	Tm Tamb
4-Transient & Fast overvoltage	MOV Metal Oxyde varistor	MOV➔Fuse
5- Short Circuit	IOCR-CB Instantaneous overcurrent relay	IOCR-CB➔Tm-CB➔F
	Fuse : F	F
-Reverse direction (N sequence)	-RDD-CB Reverse direction detector	RDD-CB