

Design, Testing Analysis of High Tension Increased Safety Motor for Hazardous areas

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Abstract

The increased safety (Ex e) motors are designed for safe operation in the zone 1 and 2 hazardous areas. The present paper describes the significant design parameters and successful testing of Ex e high tension (HT) induction motor rated 970KW/6.6KV/18 pole/ 3Phase/ 50Hz as per IS/IEC 60079-7 standard. The comparison of some useful design parameters is also given between safe area motor and hazardous area motor in this paper. The Ex e high tension induction motor mentioned in this paper have been manufactured by Bharat Heavy Electricals Ltd. (BHEL), Bhopal, India during the project and main author was the project leader.

Keywords: increased safety motor, risk factor, testing, I_A/I_N , t_E .

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1. Introduction

The hazardous atmosphere is probably due to inevitable leakages of hazardous gases during extraction/process of hazardous material. The leakage hazardous gases mixed with available air to form a potentially explosive atmosphere. Explosive atmosphere is a mixture of flammable gas, vapour, dust or mist with air, in certain proportions. The continual growth of the chemical and petro-chemical engineering industries implies a corresponding increase in the number of industrial complexes involving hazards from flammable gases, vapours and mists which can produce explosive mixtures with air. The motor, which is the work horse of driving process equipment, may be a source of energy release under normal or abnormal specified condition if motor is not designed properly for hazardous area.

A summary of the review of the possible potential sources of ignition in motor is carried out before design of the Ex e HT induction motor. It was clear from the review, that ignition tends to occur during starting conditions [1-4]. Bredthauer et al [1] observed the high circulating current induced in the machine frame components during starting. Clark et al [3] concluded that the sparking and arcing phenomenon occurs in the air gap at the end packets of the machine. Bianco et al [5] investigate the possible incendive effect due to partial discharges in the insulation system. Dymond [4, 6] indicated that contamination will lead to surface discharge and tracking on the windings, which is another potential source of sparking and arcing. Hamer et al [7] elaborated on the relationship between hot rotor surfaces and flammable vapor ignition.

The terms 'sparking', arcing and 'non-sparking' must be regarded as generic phrases covering the full range of discharge activity which could be present in the machines. The design and construction of high voltage machines, and the insulation materials used result inevitably in the possibility of electrical discharging at various locations within the machine. Discharges may occur as partial discharges in voids within insulation in the stator winding; between surfaces where an electrical stress exists, for example as a slot discharge between the slot-portion of the stator winding and the stator core; along an insulating surface at which an electrical stress exists, for example corona in the stator end-winding and core-end region; as arcing between rotor bar and rotor core within the slot; as arcing between the rotor endring and other components, such as a retaining ring, or the core or core-clamping plate; between rotor and stator due to electrical stress; All these phenomena can occur in normal operation, i.e. both

during starting and when running on load. Corona discharging may occur in stator windings, particularly on the line-end coils in the end-winding region. The energy in a corona discharge will be influenced by the local capacitance and the discharge inception voltage [8]. The partial discharge (PD) is a localized dielectric breakdown within a solid or liquid insulation under a high electrical stress. Corona discharges occur in the fluid surrounding a conductor. Corona is a form of PD that occurs in gaseous media around conductors and exhibits a certain discharge magnitude and energy. Generally, PD and corona discharges appear as short duration pulses having duration of much less than 1 μ s. Both PD and corona discharge activities are often accompanied by emission of sound, heat and chemical reaction. Corona discharges will also emit light when the electrical stress is sufficiently high. The three magnitude of discharges depends on the size of the voids within a dielectric or the gap between conductors at different potential. The quantity of discharges is related to the number of voids. Corona discharges in the external environment will be of main concern with respect to ignition of the hazardous gases [9]. The potential air gap sparking rotor assessment and potential stator winding discharge risk assessment is required to be conducted in explosive atmosphere as per IS/IEC 60079-7 [10] to confirm any occurrence of arc or spark in the motor due to corona discharge or and partial discharge. The rotor sparking takes place during starting and occurs between the rotor bars and rotor core, especially in the vicinity of the first radial cooling ducts. It is caused by movement of the rotor bars, either within the slots or around the end of the core in the area where the bar is shaped. In most cases the movement is the result of angular and radial forces which act on the rotor during starting, and it interrupts current flow from the bars to the core, causing the sparking [11].

The terminal box must be weatherproof and the enclosure must have mechanical strength and be thermally and chemically stable; these requirements are to prevent the enclosure terminals being contaminated, which could in turn lead to electrical surface tracking. The cable entry must also be via a robust weatherproof cable gland. The terminals themselves must have some anti-vibration feature to prevent them coming loose and the clearance and creepage distances must comply with a specified minimum value, depending upon the voltage between adjacent terminals. The terminal block material must comply with a minimum specified comparative tracking index, depending upon the creepage distance between terminals and the voltage used [12].

The Ex e HT motor is required to be adopted some additional requirements as per IS/IEC 60079-7. After successful relevant tests and desired performance of designed Ex e motor, it can be assured that the designed increased safety motor cannot become a source of ignition in the hazardous area during operation. A prototype 970KW/6.6KV/18 pole Ex e HT induction motor has been designed and tested as per relevant standards. The motor is designed for use in zone 2 and bearing temperature class T3 ($\leq 200^{\circ}\text{C}$) [13]. The designed parameters of motors, ignition risk assessment and relevant tests have been described in the paper. The increased safety motor is used in the zone 1 and 2 areas but in India it is limited to zone 2 area application only as per IS 5571:2009 [14]. There are some terminology for Ex e motor which are rated current (I_N), starting current (I_A), Current Ratio (I_A/I_N) and time t_E . Rated Current (I_N) is the full load current taken by the machine. Initial starting Current (I_A) is the highest root mean square value of current absorbed by an AC motor at rest when supplied at the rated voltage and frequency. Starting Current Ratio (I_A/I_N) is the ratio between initial starting current (I_A) and rated current (I_N). Time t_E is the time taken for an AC rotor or stator winding, when carrying the initial starting current (I_A) to be heated up to the limiting temperature from the temperature reached in rated service at the maximum ambient temperature. The starting current to rated current ratio (I_A/I_N) is also determined in order to provide for the selection of a suitable current detection device to protect against the occurrence of non-permissible temperatures. The length of time t_E must be such as will allow, when the rotor is locked, the motor to be disconnected by the current dependent protective device before time t_E has elapsed.

2. Comparison of Ex e Motor with Normal Motor

The comparisons also have been done on some important design parameters with the normal motor (general HT induction motor being used in the non-explosive area) and increased safety normal HT motor as given in the Table 1.

Table 1. Comparisons of design parameters between normal motor and Ex e HT motor

Design aspect and performance	Normal Motor	Ex e HT Motor
Mechanical design		
ingress protection	Depends on user	Minimum IP 54 requirement
bearing clearance	Not compulsory	It should be 0.05mm minimum as per IS/IEC 60079-7
shaft	Spider construction or solid one piece	Solid one piece
shaft assembly	Interference fitted	Interference fitted
rotor	Cast die aluminium or copper bar	Copper/brass bar
radial air gap	Gap=0.2+2√DL, where D=rotor diameter in mm, l= core length in mm [15]	As per equation (1) of this paper
cooling	Good cooling	Good cooling
risk factor (cooling duct)	Not applicable	It is applicable
Fan and fan cover clearance	Fan should not come in contact of fan cover	Minimum 1mm and maximum 5mm
Fasteners	General fasteners can be used	It should be as per ISO 262, ISO965-1 &3, ISO 4014, ISO 4017, ISO 4032, ISO 4026, ISO 4027, ISO 4028 or ISO 4029
Impact withstanding capacity	Not applicable	It is conducted as per IS/IEC 60079-0
Cable gland	Normal weatherproof cable gland	Ex e certified and approved cable gland
Electrical Design		
creepage distance & clearance	Not compulsory	It is mandatory
anti-loosening & vibrationproof terminals	Not applicable	It is a must
stator winding conductor size	Not compulsory	Minimum 0.25mm size
insulation class	As per IS/IEC60034-1 [16]	As per IS/IEC 60079-7
temperature class specification	No temperature class specification	T1-T6 class as per IS/IEC 60079-0
limiting temperature of insulation class	As per IS/IEC60034-1	As per IS/IEC 60079-7
space heater	It may be or may not be	Provision is must for >1KV operating voltage
risk factor (rotor cage construction, pole, rated output, rotor/stator skew, rotor overhang parts)	Not applicable	Consideration of risk factor is mandatory
Risk assessment	Not applicable	It is must
Protection for abnormal condition, overload	Protection is required	Protection must be provided
Performance		
Speed-torque characteristics, efficiency & p.f.	As per IS/IEC 60034-1	As per IS/IEC 60034-1
t_E	Not applicable	It is must and it shall be minimum 5seconds
I_A/I_N	Not applicable	It is must and it shall not be more than 10
Use/application	For safe area application	For hazardous area application

Generally the following reasons may be the cause for explosion by the motors.

- Surface temperature due to inevitable losses causing heat penetration, but inadequate ventilation
- Generation of sparks between live terminals and earth
- Partial discharges occurring in embedded insulation in slots
- Housing currents due to stray leakage flux
- Sparks in air gap of high-speed machines due to vibration of cage bars

While designing of Ex e motor all above measures have been considered to avoid arc/spark and hot surfaces in the motor.

3. Electrical Input and Output for Ex e Motor

The parameter is furnished by the end user as per his requirement for particular application and on the basis of input the motor is being designed. The basic input parameters are required to design an increased safety motor are voltage, full load current, frequency, phase, power factor (p.f.), torque, speed, efficiency (η), Horsepower (HP) or Kilowatt (KW) rating etc. The voltage and frequency tolerance for this motor is $\pm 5\%$ and $\pm 2\%$ respectively and

it is qualifying the requirement of IS/IEC 60034-1. The duty cycle is the length of running time in which the motor can carry its full load safely. Most often, this is continuous. Some applications have only short-time (S2) or periodic duty (S3-S10) use and do not need motor full-load continuously. The present Ex e motor is designed for continuous duty (S1). The reliability of motor is dependent generally on the insulation class of the motor winding, maximum ambient temperature and altitude. The 'F' class insulating material is used for windings of the 970kw Ex e motor. The motor is designed for maximum ambient temperature of 40°C and altitude below mean sea level.

4. Risk Factor of 970kW Ex e Motor

The IS/IEC 60079-7 includes ignition risk assessment for rotor cage and stator of increased safety motor. In order to confirm that the stator winding is free from ignition due to partial discharges at the rated voltage of machine so ignition risk assessment is required [17]. The risk factors are dependent on the different characteristics of the motor from design to end use. The detail of the risk factors for cage rotor is given in Table 2 for 970kw Ex e motor. If the total sum of risk factor is greater than 6 then the motor should be assessed for airgap sparking risk assessment as per IS/IEC 60079-7:2006. It is clear from the Table 2 that total sum of risk factor of 970kw motor is 7 which is greater than 6, hence 970kw designed motor should be assessed for airgap sparking risk assessment by conducting impulse test and high voltage test in explosive environment.

Table 2. Characteristic risk factors for rotor of 970KW Ex e motor

Characteristics as per IS/IEC 60079-7	Value specified in the IS/IEC 60079-7 for risk factor		Risk factor for 970KW
Rotor cage construction	Uninsulated bar Fabricated rotor cage	3	2
	Fabricated rotor cage	2	
Number of poles	> 8 pole	0	0
	2 pole	2	
Rated output	≤200KW per pole	0	0
	>500KW per pole	2	
Radial cooling ducts in rotor	Yes: $L < 200\text{mm}$	2	2
	Yes: $L \geq 200\text{mm}$	1	
Rotor or stator skew	NO	0	2
	Yes: >200KW per pole	2	
Rotor overhang parts	Complaint	0	0
Limiting Temperature	$135^{\circ}\text{C} < T \leq 200^{\circ}\text{C}$	1	1
Total factor			7

5. Design Parameters of 970kW Ex e Motor

While designing Ex e motor special measures are given on following aspects:

- Risk factor assessment
- Ignition potential risk assessment
- Temperature rise of all the parts under normal and abnormal operating conditions
- Spark producing properties of material used in the construction
- Enclosure design
- Mechanical clearances between stationary and rotating parts
- Creepage distance and clearance with respect to CTI (comparative tracking index) level of insulating material of terminal blocks

5.1. Stator and Stator Frame

The problem of ignition due to sparking resulting from interruption of circulating joint discontinuities is not confined therefore to rotating machines [18]. The stator and stator frame is designed in such a way that they cannot produce more circulating current which can cause for ignition. The stator contains the primary winding and is made up of laminations with a large hole in the center in which the rotor can turn. There are slots in the stator in which the windings of the coils are inserted. The cast housing to receive the stator stamping packs, two pot end shields is made of grey cast iron and two bearing heads. The stator housing made of stainless

steel consists of a welded construction. The end shields are designed as discs and receive the bearing heads. These construction elements are screwed together axially. A continuous centering of the assemblies one by one makes an air gap check unnecessary even after disassembly. Radially arrayed guides ensure an exact tangential positioning of the end shields with the stator housing after disassembly. The stator stamping pack is fixed in the housing via a press fit and then spooled. The stamping pack is put together out of insulated dynamo sheet round plates or overlapped dynamo sheet segments and axially tensioned over end plates with press pins. The stator pack is shrunk in the stator housing. A press spring is used to receive the short-circuit moment. A continuous centering of the assemblies one by one makes an air gap check unnecessary even after disassembly.

5.2. Insulation System

The insulating system is the important part of the design for the Ex e HT motor which can withstand risk ignition assessment tests at high and impulse voltages. The insulating system of the winding of motor is served the purpose to:

- a) separate the various electrical components from one another, and
- b) protects itself and the electrical components from attack of contaminants and other destructive forces.

Five specialized elements are employed that constitute insulation systems of motor winding which are given below:

- a) *Turn to turn insulation*- The insulating material is installed between separate wires in each coil. In this case the conductors of winding is tapped as the insulation.
- b) *Phase to phase insulation*-In this case the insulation is installed between adjacent coils in different phase groups. The wound coil of stator is wrapped with insulating tape turn to turn.
- c) *Phase to ground insulation*—This insulation is installed between the motor windings as a whole and the “ground” or metal parts of the motor. Typically, a sheet of insulating material is provided in the stator slots to provide both dielectric and mechanical protection.
- d) *Slot wedge*—This insulation is used primarily to hold the conductors firmly and tightly in the slot.
- e) *Impregnation*—This process is used to bind all the other insulating components together and fill in the air spaces within the applied insulating materials. This process is applied in fluid form and then cured (hardened) to provide electrical, mechanical, and contaminant attack protection.

By providing proper insulation in the different locations of the motor so this insulation systems has made this design possible and this insulation system could sustain potential ignition risk assessment as per IS/IEC 60079-7:2006. The insulation class F has been used and confirmed for design of 970KW Exe HT induction motor and functional evaluation of this insulation system is qualified as per IEC 60034-18-31 [19]. The name of this insulating system is Resin Poor class F Micalastic (Vacuum Pressure Impregnated) Insulation and which is also qualified for wet test as per NEMA specification MG 1-20.48(9) [20], lightning and switching surge voltage test as per IEC 60034-15 [21] and low dissipation factors as per VDE 0530.

5.3. Rotor Construction

The rotor is the rotating part of the Ex e induction motor and it is made of stacked laminations. A shaft runs through the center and a squirrel cage made of copper bars holds the laminations together. The squirrel cage acts as a conductor for the induced magnetic field. The bars are in direct contact with the core, which allows for faster heat conduction. The rotor construction can be either a solid shaft or welded ribbed shaft depending on machine size. The rotor stamping pack consists of dynamo sheet round plates or overlapped layered dynamo sheet segments. The stamping pack is tensioned axially with press pins. Stamping packs consisting of round plates are shrunk onto the shaft. Stamping packs made up of segments are laminated onto dovetail-shaped strips of the ribbed shaft. Rotors with ribbed shafts have a feather key to receive the short-circuit moment. A photograph of rotor of Ex e HT motor is shown in the Figure 1.

The rotor bars made of copper are inductively soldered axially with the protruding short-circuit disks. The special shape of the short circuit disc and the rotor rods ensures a high

soldering quality. The outer contour of the short circuit discs is worked on only after the soldering is complete in order to achieve an optimal pre-balancing condition. The rotor bars are properly locked to prevent any spark from the rotor during operation.



Figure 1. View of rotor assembly of motor

5.4. Stator Winding

The double layer lap winding is used for this Ex e motor. The three-phase double-layer lap winding lies in the open grooves of the stamping pack. It is designed as a whole pulled coil. Flat copper wire, insulated with mica foil, is used for the entire pulled coils. The main insulation of the coils consists of low adhesive mica-fibreglass tape. To avoid corona discharges, installed in the slot part is a low impedance and in the slot exit a high impedance mica protective cover. The completely insulated conductor packages are fixed in the slots using slot connectors made of glass fabric and epoxy resin. The switch connections are hard-soldered at the whole pulled coil windings. A photograph of stator winding of Ex e HT motor is shown in the Figure 2.

The completely wound stator stamping pack with housing is thereby impregnated in an epoxy-resin bath first under vacuum and then under pressure. The subsequent heat treatment hardens the resin. A cavity-free winding insulation and a bonded stamping pack are thus guaranteed free from any void or moisture. The winding and the slot wedges are likewise fixed with the epoxy resin in the stamping pack. The winding heads are able to take up large deformation forces, which can be caused by load shocks and mains switch-ons.

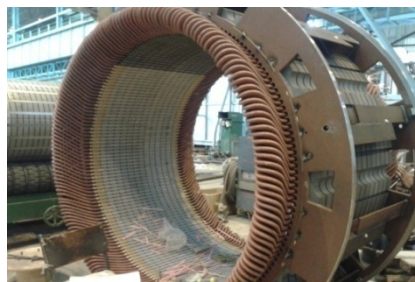


Figure 2. View of stator assembly of motor

5.5. Shaft Construction

The material for shaft is hot rolled steel with a tensile strength of about 100,000 psi, is used. The material strength and shaft size are determined to withstand 11 times rated torque. The shaft of motor is turned and ground to tight tolerances that help eliminate rotor core runout and unbalance of the final rotor assembly. For this motor a solid shaft (4150 steel grade) is used.

5.6. Shaft Assembly by Interference Fit

The rotor of Ex e motor is heated and assembled to the shaft with an interference fit. The interference fit creates a uniformly distributed force between the shaft and rotor. This force restricts the rotor from spinning on the shaft.

5.7. Radial Air Gap

The radial air gap between stator and rotor of increased safety motor is very important for consideration during design to avoid sparking and arcing in the air gap at the end pockets of motors. The minimum air gap is calculated on the basis of Equation (1).

$$\text{Air gap} = \{0.15 + [(D-50)/780] [0.25 + (0.75 \times n/1000)]\} r y \quad [10] \quad (1)$$

Where,

D = rotor diameter in mm (subject to a minimum of 75mm and a maximum of 750mm)

r = core length/(1.75 × D)

n = maximum rated speed in RPM and y= 1 for motor with rolling bearing or 1.5 for plain bearing

The air gap is generally kept higher than the calculated value for Ex e motor [22]. The designed radial air gap value is more than the calculated value as per the standard IS/IEC 60079-7. The radial air gap value of 970KW Ex e motor under discussion is calculated by using Equation (1). The value of different design parameters are tabulated in the Table 3.

Table 3. Radial air gap design parameters of Ex e motors.

Motor rating	D in mm	n in RPM	Core length in mm	y	r	Calculated Air gap as per Eqn. (1) in mm	Maintained air gap in the designed Ex e motor in mm
970 KW	700	330	920	1	0.751	0.423	2.5

5.8. Terminal Enclosure for Winding Connections

The connecting boxes are designed and tested for IP55 ingress protection as per IS/IEC 60529-2001 for weatherproofness. The connecting box is welded in construction and have an earthing terminal in the bottom part. The bottom part is screwed to the connecting flange of the housing. The connecting boxes with terminal arrangement in accordance with DIN 42962 and it can be turned 90° and 180°. The short-circuit-resistant cast-resin insulators are provided within the enclosure for connecting the power cable to the motor. The cast-resin insulators can handle short-circuit current up to 50 kA for 0.2 s.

5.9. Rotor Ventilation

The maximum cooling is provided by proper venting of the rotor core. The solid lamination maximizes the shaft to rotor contact area, increasing the rotor core stiffness. The rotor is cooled by axial flow of air through the air gap between the rotor and stator. The cooling is achieved by airflow around the end rings and axial flow through the air gap. Heat is removed from the rotor by convection and conduction through the stator core and finned frame. In addition to the laminations with radial ducts, special spacer laminations are placed at several locations along the axial length of the core. The spacer laminations ensure cool air circulation past the rotor bars and through the stator windings. This design allows a generous flow of air through the center of the rotor core.

5.10. Cooling

The cooling of the motor is designed as TETV (totally enclosed and totally ventilated) heat exchanger. It is air-to-air cooling, the motor exhaust flows through a hood, which is designed as a welded structure. In this hood, stainless steel tubes whose ends are welded into the end faces of the hood. This structure forms the air-to-air heat exchanger. The motor exhaust flows around the tubes and is cooled down through the secondary air flow within the tubes. The secondary internal air flow is thereby fed through a certified and approved flameproof (Ex 'd') fan. The secondary Ex 'd' fan is covered by a hood with intake. The inner cooling circuit is

separated from the surroundings through sealing measures according to the motor protection class.

5.11. Bearings

The roller type bearings are provided in the motor as locating bearings (double bearing) on the drive end side and the floating bearings on the non-drive end side.

5.12. Motor Name Plate

The brass made name plate of 970KW Ex e HT motor is provided on the stator body of the motor and it represents the details of motor and data of name plate is always useful for future references. The increased safety motor must have detail of motor like, horsepower/kilowatt, voltage, speed, pole, full load current, type of protection, frame size, manufacturer's designation, marking, warning inscription, standard reference, Ingress protection (IP), phase, frequency, insulation class, maximum ambient temperature, power factor, efficiency, bearing detail, t_E , I_A/I_N , test certificate number, approval number and additional information as per IS/IEC 60079-0, IS/IEC 60079-7 and IS/IEC 60034.

5.13. Warning Inscription

The warning inscription is provided on the motor as "MOTOR SHOULD NOT BE OPENED IN ENERGISED CONDITION IN EXPLOSIVE ATMOSPHERES".

6. Testing of Ex e HT Motor

All the relevant tests have been conducted successfully on the designed 970kw Ex e HT motor. The high voltage test, locked rotor test (for measurement and determination of rate of temperature rise for the stator and rotor, starting current ratio I_A/I_N and time t_E), no load test, performance test/load test, temperature rise tests, vibration test, noise level test, test for ignition risk assessment and other relevant tests are conducted on the 970kw Ex e motor by using IEC 60034 and other relevant standards. The 970kw Ex e HT motor have been passed all the tests conducted as per requirement of standards. The details of the some test are given in this paper.

6.1. Impulse Voltage Test Assessment

The impulse voltage test assessment is done to prove the capability of the insulation system to withstand over voltages (due to lightning and switching surges) that may appear across it while in operation. The impulse test was carried out at BHEL, Bhopal with the help of a special 200 kV - 2 stage impulse generators [23]. The prototype sample coil (one complete stator) was produced for 970KW motor. The coil was placed in the box and electrical connections were made with the impulse generator. The coil was placed in the explosive gas mixture comprising of $21 \pm 5\%$ hydrogen in air. The 16.2KV impulse voltage was applied phase to phase and separately phase-to-earth on the coil of motor in the explosive atmospheres. There was no ignition occurred in the explosive test mixture during the testing in any case when 10 impulses of 16.2kV were applied. The coil of motor withstood the ten impulses of desired magnitude successfully as per clause 6.2.3.1.4 of IS/IEC 60079-7:2006. The photograph of coil sample is shown in the Figure 3.

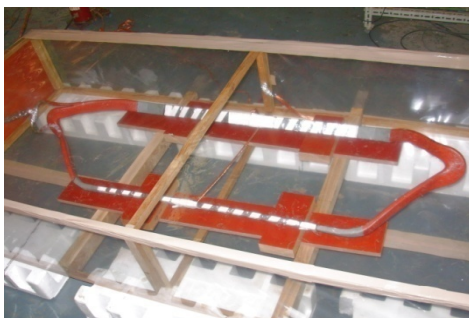


Figure 3. Sample of one coil of 970KW Ex e motor

6.2. High Voltage Test Assessment

The High voltage testing and assessment has been done successfully to prove the high voltage withstanding capability of 970kw Ex 'e' HT motor winding insulation system. The prototype stator capsule (one complete stator) was prepared for 970kw motor to conduct the high voltage on it. Then the coil was placed inside the test setup box and electrical connections were made to the high voltage equipment. The test setup box was contained explosive atmospheres of 21% hydrogen in air. The sinusoidal voltages of 10kV r.m.s (1.5 times of rated voltage) was applied on stator capsule winding of the motor rated 970KW, 6.6 kV, 3-phase, 50 Hz for three minutes duration between one phase and earth with the other phases earthed. No explosions were observed in the box during this test. The maximum rate of voltage rise was measured 0.5kv/second.

6.3. Stator Winding Temperature Rise

The cold resistance of stator winding and motor temperature was measured and recorded. Then motor was run for several hours at full load until thermal stabilization was attained. The temperature of stator body at every half an hour interval was taken. When the temperatures reading of stator body between two consecutive readings were same then it was confirmed that the motor was thermally stabilized. The motor was then switched off and hot resistance of stator winding was measured within the specified time and accordingly temperature rise of stator winding is calculated by resistance method as per Equation (2) [24].

$$\text{Temperature rise } T_R = [(R_{hot} - R_{cold}) / R_{cold}] \times (235 + t_1) + (t_1 - t_a), \quad (2)$$

Where,

R_{cold} = Cold resistance of stator winding of motor in Ω = 0.278 Ω ,

R_{hot} = Hot resistance of stator winding of motor in Ω = 0.323 Ω ,

t_1 = Machine Temperature at the initial cold resistance measurement in $^{\circ}\text{C}$ = 29 $^{\circ}\text{C}$,

t_a = Ambient temperature at the end of the examination corresponding to hot resistance in $^{\circ}\text{C}$, = 27.6 $^{\circ}\text{C}$,

Temperature rise (T_R) = [(0.323 – 0.278) / 0.278] \times (235 + 29) + (29 – 27.6) = 44.13 $^{\circ}\text{C}$.

6.4. The time t_E for stator of 970KW Ex 'e' motor

Rate of temperature rise:

$$\Delta\theta / t_E = a \times j^2 \times b, \quad [24] \quad (3)$$

And it can be written as:

$$t_E = \Delta\theta / (a \times j^2 \times b), \quad (4)$$

Where,

$\Delta\theta$ = Temperature difference between limiting temperature and total temperature determined by resistance method in $^{\circ}\text{C}$,

Total temperature (T) = temperature rise determined by resistance method (T_R) +

Ambient temperature (T_A)

a = 0.0065 for copper $^{\circ}\text{C} / (\text{A}/\text{mm}^2)^2 \text{ sec.}$,

b = 0.85 reduction factor for heat dissipation ,

t_E = time in second ,

j = Current density at starting in A/mm^2 ,

The time t_E of stator winding is calculate by using equation (4) and determined value is specified in the Table 4.

Table 4. Time t_E for stator winding of 970KW Ex 'e' motor

Starting current	Cross sectional area of winding conductor	Current density	Ambient temperature	T_R	T	Limiting temperature	$\Delta\theta$	t_E as per equation (4)
545.7A	41.3mm ²	13.21A/mm ²	40 $^{\circ}\text{C}$	44.13 $^{\circ}\text{C}$	84.13 $^{\circ}\text{C}$	170 $^{\circ}\text{C}$	85.87 $^{\circ}\text{C}$	89.44 seconds

6.5. Time t_E for Rotor of 970KW Ex e Motor

The above motor is designed for temperature class T3 (200°C), hence limiting temperature is 200°C and maximum ambient temperature of 40°C. The cage rotor temperature rise of Ex e HT induction motor can be calculated with the help of Joules effect heat balance equation as given below:

$$m \times s \times \Delta\theta = b \times I^2R \times t_E, [24] \quad (5)$$

Where,

m = mass of cage winding = 469.7 Kg ,

s = specific heat of copper = 0.396 ,

b = ventilation factor = 0.85 ,

I^2R = copper loss in rotor winding = Starting torque \times KW of motor ,

$\Delta\theta$ = Maximum allowable temperature (T3 class) – Maximum rated operating temperature (for insulation Class B) ,

The time t_E of rotor winding is calculate by using Equation (5) and calculated value is specified in the Table 5.

Table 5. Time t_E for rotor of 970KW Ex e motor

Mass of rotor winding	Starting torque	Kw of motor	Maximum allowable temperature (T3 class)	Maximum rated operating temperature	$\Delta\theta$	t_E as per equation (5)
469.7 Kg	107.6%	970Kw	200°C	120°C	80°C	16.77 seconds

7. Result and Analysis of 970kW Ex e Motor

The relevant test and some calculations are carried out on designed 970kw Ex e motor. The different important parameters of designed motors are given in the Table 6.

Table 6. Different parameters of 970 Ex 'e' motor

Parameters	970KW Ex e HT motor	End user or standard requirement
Temperature rise at full load	44.13°C	70°C
Time t_E for stator	89.44 sec	≥ 5 sec
Time t_E for rotor	16.77 sec	≥ 5 sec
Time t_E for tripping device of Ex e motor	≤ 16.77 sec	≥ 5 sec
Efficiency at full load	95.86%	$\geq 94.0\%$
Pull out torque in p.u.	2.388	2.3 p.u. (per unit)
Speed at Full load	330.7 rpm	330 rpm
Slip at Full load	0.00789	0.008
Starting current	545.7 A	550 A
Starting torque in p.u.	1.076	1.0 p.u.
Power factor at full load	0.739	0.72
Core losses at no load	10.86KW	≤ 12 KW
Stator copper losses at full load	14.66KW	≤ 16 KW
Rotor copper losses at full load	8.0KW	≤ 10 KW
Ratio Starting current/rated current (I_A/I_N)	4.23	≤ 10
Total Iron and Cu losses	33.52KW	≤ 38 KW

It has been observed that starting torque, total losses, speed at full load, temperature rise, starting current, current density, efficiency, time t_E of stator, time t_E of rotor, power factor and full load slip all are the well within the limit and as per the requirement of the end user as shown in the Table 6. The analysis of some parameters and results are given below:

- The stator winding of the prototype designed motor sustained successfully impulse voltage test at 16.2kv and high voltage test at 10kv in 21% hydrogen atmospheres.
- The designed radial air gap is more than the calculated value and maintained 2.5mm air gap to avoid any sparking between rotor and stator during running the motor.
- Iron loss are reduced by utilizing high grade silica steel.
- The I_A/I_N ratio is 4.23 which is less than 10.

- e) Time t_E of designed motor is 16.77 seconds which is more than 5 seconds.
 f) Temperature rise of stator winding is 44.13°C which is much less than 70°C limit value.

The Table 7 shows as load is increased the efficiency and power factor of the motor increases. The efficiency and power factor of 970kw Ex e motor are 95.9% and 73.9% respectively at 100% rated load. The torque, current and full load speed characteristics are shown in the Figure 4 which compiles the requirement of induction motor and user as well. It is clear from the Figure 4, the starting torque of motor is about 80% of full load torque (FLT) and maximum motor torque is 250% FLT at 100% rated voltage.

Table 7. Load, efficiency and power factor parameters of 970 Ex e motor

Load %	970KW/6.6kv/18pole motor Efficiency %	% p.f.
25	91.9	33.3
50	95	55.3
75	95.8	67.6
100	95.9	73.9
125	95.88	70.6

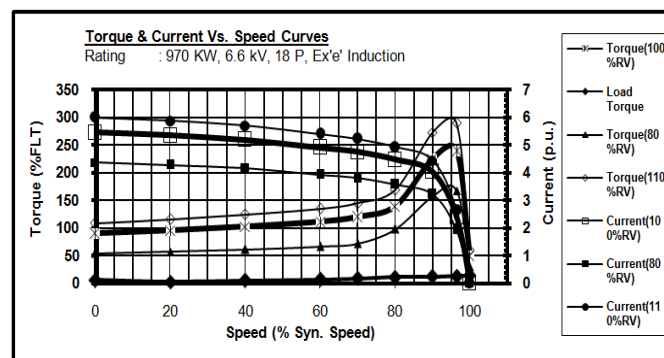


Figure 4. Torque, speed and current characteristics of 970KW Ex e Motor

4. Conclusion

The motor has unique characteristics as per requirement of the load and the load requirement has been taken into consideration during design of the prototype Ex e 970kw HT motor for hazardous area. The impulse voltage assessment and high voltage test assessment in hydrogen atmospheres have been conducted successfully for the windings of the designed aforesaid motor. As per the design of the Ex e HT induction motor described in the paper, maximum rotor time t_E is 16.77seconds which is more than the standard requirement as 5 seconds. The temperature rise of stator winding is also achieved 84.13°C at 40°C ambient temperature which is less than the 110°C. The starting current ratio (I_A/I_N) is 4.23 which is less than 10 as specified in the IS/IEC 60079-7. The performance characteristics of the designed 970kw Ex e HT motor also meets the load demand as per the end user requirement. The designed motor is running successfully in an Indian oil industry in zone 2 hazardous area.

References

- [1] J Bredthauer, LB McClung. Risk of ignition due to transition currents in medium voltage motors for classified locations. *IEEE PCIC*. 1990.
- [2] J Bredthauer, N Struck. Starting of Large medium voltage motor: Design, protection and safety aspects. *IEEE Transactions on Industry Application*. 1995; 21: 1167-1176.
- [3] P Clark, N Glew, R Regan. Solutions for MV motors and generators in hazardous locations. *IEEE PCIC*. 1996.
- [4] JH Dymond, K Younsi, N Starnages. Stator winding Failures: Contamination, surface discharges and tracking. *IEEE PCIC*. 1999.

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- [5] L Bianco, F Feudale, F Razza, M Sica, A Contin, G Rabach. High voltage induction motors for use in hazardous area: Evolution of legal aspects and technical investigations related to safety problems. *IEEE Conf. publication 390*. 1994.
- [6] JH Dymond. Sparking, Electrical discharge and heating in synchronous and induction machines: Can it be controlled?. *IEEE Transactions on Industry Application*. 1998; 34(6).
- [7] PS Hamer. Flammable vapor ignition initiated by hot rotor surface within an induction motor-reality or not?. *IEEE PCIC*. 1997.
- [8] Saeed Ul Haq, Bharat Mistry, Ramtin Omranipour. *How safe is the insulation system of rotating machines operating in gas groups b, c & d?*. IEEE International conference PCIC. 2011.
- [9] M Bradford, AL Bartels, WN Povall. Type 'e' and type n electrical machines in hazardous areas: a safety review. *IEEE*. 1994: 69-78.
- [10] Electrical apparatus for explosive gas atmospheres- Increased safety. 2006.
- [11] Jussi Rautee, Frank Lienesch, Tom Liew. Safety improvements of non-sparking and increased safety motors.
- [12] Colin Grantham. Electrical Machines and Drives for Potentially Explosive Atmospheres. *Journal of International Conference on Electrical Machines and Systems*. 2012; 1(1).128-134.
- [13] Electrical apparatus for explosive gas atmospheres-General requirements. 2004.
- [14] Bureau of Indian Standards (BIS) IS 5571. Guide for selection and installation of electrical equipment in hazardous area (other than mines. 2009.
- [15] MG Say. Performance and design of AC machines. Pitman Publication, London.
- [16] IS/IEC 60034-1. Rotating electrical machines-Rating and performance.
- [17] Bharat Mistry, William G Lawrence, Evans Massey, Paul S Hamer. *Proposed revisions to IEC 60079-15 how has harmonization affected Ex nA motors?*. IEEE International conference PCIC. 2009.
- [18] PE Clark. Developments in the certification of Exn motors. *The Institution of Electrical Engineers, IEE*. London. 1999: 411-414.
- [19] IEC 60034-18-31. Rotating electrical machines-Functional evaluation of insulation systems - Test procedures for form-wound windings - Thermal evaluation and classification of insulation systems used in rotating machines.
- [20] A.C. High potential test. NEMA MG. 48(9): 1-20.
- [21] IEC 60034-15. Rotating electrical machines- Impulse voltage withstand levels of form-wound stator coils for rotating a.c. machines.
- [22] Raymond Ong, JH Dymond, Bharat Mistry. *Design of increased safety electrical machine: development activities and certification testing*. IEEE International conference PCIC. 2000: 65-75.
- [23] Bhagirath Ahirwal, TK Chatterjee, AK Singh. Assessment and control of ignition risk of HT induction motor for increased safety Ex 'e' as per Indian standard for explosive atmospheres. *IEEE PSES*. 2011: 1-5.
- [24] B Ahirwal, AK Singh, RK Vishwakarma, A Sinha. Increased Safety Protection and Energy Conservation for Motors installed in Zone 1 & 2 Hazardous area using variable Speed drives (VSDs). *International Journal of COMADEM*. 2009; 12: 15-23.