DESIGN, ANALYSIS AND COMPARISON OF METHODS TO INCREASE TIME t_E OF INCREASED SAFETY MOTOR FOR HAZARDOUS AREA

Dr. Bhagirath Ahirwal *, Dr. Tarun Kumar Chatterjee [†], Dr. Arvind Kumar Singh [$]

* Principal Scientist, CSIR-Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad, (JH)-826015, **(Corresponding Author)**, Phone: +91-326-2296025, Fax: +91-326-2296019
E-mail: ahirwalcmri@yahoo.co.uk
[†] Professor, Electrical Engineering Department, Indian Institute of Technology, Dhanbad, (JH)-826001,
[$] Sr. Principal Scientist, CSIR-Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad, (JH)-826015,

Abstract- *High Voltage (HV) increased safety (Ex e) motors are being designed for safe operation in the hazardous area. The motor time t_E for increased safety motor is prime safety parameter. The higher value of time t_E means insulating system of Ex e motor is able to withstand the locked condition for long time so motor will be more safe for long duration during in abnormal condition in hazardous area. The research work shows that the time t_E of Ex e motor can be increased by increasing the mass of rotor bar or by increasing the stator coil pitch. Low speed and a high speed HV Ex e motor were selected to redesign with increasing rotor bar mass and stator coil pitch. The time t_E and other parameters of redesigned motors have been compared with standard design of Ex e motor. It is anticipated that this study will be of immense benefit to Ex e HV motor designers.*

Keywords: *Increased safety motor, time t_E, temperature rise, air gap.*

1. Introduction

The increased safety is a complete inbuilt method of protection in which equipment is specially designed to prevent any arc, spark or excessive temperature. Increased safety protection method is widely being used to make Exe junction boxes and motors for safe operation in zone 1 and 2 hazardous area. The Ex e equipment is applicable only for use in zone 2 area in India as per IS 5571 [1]. The motor time t_E is higher means motor can withstand thermal stability of winding insulation for long time without insulation failure in abnormal specified condition. The limiting temperature of insulation of winding of motor is dependent on the time t_E. The time t_E is the time which is taken by motor to start or rotor locked without producing any arc or spark or failure of insulating material of Ex e motor winding. The time t_E of motor should be more than 5 seconds. Increased safety is a protection in which additional measures are applied so as to give increased security against the possibility of excessive temperatures and of the occurrence of arcs and sparks in normal service or under specified abnormal conditions at rated voltage assigned by the manufacturer. The temperature rise of the conductor bar for Ex e HV motor shall not exceed 45ºK at a test current of 110% of rated current according to the method of the temperature rise test as specified in IS/IEC 60079-7 [2]. The design of Ex e HV motor has certain limitation for temperature limitation with respect to insulation of winding, rotor design, termination, enclosure, performance for hazardous area. The design of Ex e HV motor also depends on the rated voltage, pole, installation, ingress protection etc. which are considered based on the risk factor. The high voltage rating of Ex e motor generally are 3.3kV, 6.6kV and 11kV but generally 6.6kV rating demand is more in the hazardous area. It has been reviewed that the current in the stator end winding, produces stray field components. These components together with leakage components due to stator core magnetic saturation induce circulating current to flow in any closed conducting circuits. The current causes arcs and sparking at the joints of a multi-section motor enclosure [3, 4]. The stray end winding field will be the strongest during locked rotor and starting conditions. Sparking may also occur across the air gap due to the movement of the bars due centrifugal and electromagnetic influences. Sparking generally occurs during the starting condition [4, 5]. Corona discharges and surface tracking on contaminated winding can also cause sparking. The phenomenon of sparking and arcing could pose a hazard in explosive atmosphere [5, 6]. When three-phase induction motors are properly designed, built, installed, and maintained, uncontained sparking is not expected except at higher speeds and higher voltages [7]. The level, when higher voltages and higher speeds, induce sparking varies greatly with the design [8]. The stator sparking can occur at any time during motor operation. The risk is increased by transients from the network, surface contamination and ageing. Rotor sparking results from the intermittent breaking of the contact between the rotor bars and core. It occurs during starting only, and is limited to the first sections of the rotor core. Manufacturers can prevent rotor sparking by taking steps during design and production to ensure that the rotor bars are properly locked. In some cases the bars are swaged into the slot for this purpose [9]. The rotor and stator type tests are required to prove that machines are not even able to ignite an explosive gas atmosphere inside of them [10]. The stator winding of HV motor shall be designed to assess for permissible breakdown impulse voltage in explosive gas mixture without failure of stator winding [11].

Time t_E is the time taken by AC windings to reach the limiting temperature of winding insulation at rated operating conditions during starting or stalling. The t_E is very important parameter for Ex e motor. The higher value of t_E of rotor and stator indicates good quality of insulation system design. It also reflects that motor cannot produce any arc, spark or excessive temperature during specified abnormal locked condition. The Ex e HV motor should be designed with respect to these objects. The time t_E of rotor winding of increased safety motor depends on the different parameters like mass of rotor bar, specific heat of winding material, heat dissipation factor and rotor copper loss or starting torque of motor. The time t_E of increased safety motor can be increased either by increasing rotor bar mass or by reducing starting current and or increasing stator coil pitch. There are two methods namely by increasing rotor bar mass and by increasing stator coil pitch are proposed to increase motor time t_E of Ex e HV induction motor. The objectives of this paper are as follows;

a) to find out the effect of increased rotor bar mass of motor on the time t_E, temperature rise and performance of motor.

b) to find out the effect of increased stator coil pitch on the time t_E, temperature rise and performance of motor.

The Ex e three phase HV squirrel cage induction motors of rating 970kW,6.6kV,18 pole (low speed motor) and 2200kW,6.6kV,2 pole (high speed motor), 50Hz are chosen and the same motors are redesigned with increase in rotor bar mass and stator coil pitch as per additional requirement of IS/IEC 60079-7. The rating and frame size of both the motors are kept same in both the cases. The comparison of performance parameters between these two proposed methods are discussed in the paper. The motors under discussion are manufactured by Bharat Heavy Electricals Limited (BHEL), Bhopal, India during the consultancy project and main author was a project leader.

2. Methodology of design of Ex e motor

As we know that heat balance equation is

$$m \times s \times \Delta\Theta = t_E.b.I^2R \quad [12] \qquad (1)$$

So equation (1) can be written as

$$t_E=(m.s.\Delta\Theta)/(b.I^2R) \qquad (2)$$

and it is known that I^2R = Starting torque.kW rating of motor, so by putting the value of I^2R in equation (2)

$$t_E = (m.s.\Delta\Theta) / (b.\text{Starting torque.kW rating of motor}) \qquad (3)$$

where, m = mass of cage winding, s = specific heat of copper, b = ventilation factor, I^2R=copper loss in rotor winding, $\Delta\Theta$ = temperature difference and t_E = time.

If s, $\Delta\Theta$, m, b and kW rating of motor are constant for a particular motor design, so Eq. (3) can be written as $t_E \propto 1$ / Starting torque i.e. time t_E is inversely proportional to starting torque of the motor. If the stator coil pitch of the motor is increased then effective number of turns increases causing increase of reactance and hence starting current will decrease. If the starting current decreases so starting torque of motor is also decreased. Hence, time t_E of motor may be increased by decreasing the starting torque of the motor upto optimization limit by increasing the coil pitch of stator.

Similarly , in the same manner if s, $\Delta\Theta$ and b are constant for particular motor design in the above equation (2) so it can be written as $t_E \propto m/I^2R$ i.e. time t_E is proportional to the mass of rotor winding and inversely proportional to rotor copper loss (I^2R). Hence time t_E of Ex e motor can be increased by increasing the rotor winding (bar) mass.

3 Important Design parameters of Ex e HV motor

Ex e motor depends on mainly stator winding, rotor winding, air gap and other parameters. Some important design parameters are described here.

3.1 Stator windings

The insulation system of stator winding should be designed in such way that it could sustain voltage impulses in the explosive gas mixture [13]. The insulated winding conductors are covered with two layers of insulation in which only one layer is enamelled. The enamelled winding conductors are confirmed with the requirement of IEC 60317-3, IEC 60317-7, IEC 60317-8 and IEC 60317-13 standards. The minimum nominal conductor dimension of wires is used for windings is more than 0.25 mm. The detail of stator winding coil profile and stator slot profile is shown in the Fig. 1 and Fig. 2 respectively. It is the lap winding and shape of coil is diamond pulled type. A coil in double layer winding represents the entire set of conductors in one slot layer in association with similar set in other layer of another slot. The number of coil is therefore same as number of slots. The lap winding for stator winding is chosen to take the maximum number of parallel paths equal to number of poles, thus resulting in optimum design without using bulky conductors. The coils are usually short pitched in order to reduce the amount of copper in the end connections and to minimize certain harmonics in the phase voltages. The phase spread is kept 60º to get a distribution factor of 0.955. The windings are star connected so the phase voltage will be $1/\sqrt{3}$ of line voltage, hence, corresponding insulation thickness of coils is reduced.

The windings are wrapped and fastened properly then it is dried to remove moisture before impregnation with a suitable impregnating substance to achieve good cohesion between the conductors. The sensing elements of resistance temperature detectors (RTDs) are sealed and impregnated with the windings. It is provided to protect the winding limiting temperature which does not exceed 200°C in any condition so the design of motor is considered for T3 temperature class [14]. The allowable current density (δs) in stator winding of induction motor lies between 3 to 5A/mm^2. The designed current density of stator winding in the designed motor is between 1.88 and 3.04 A/mm^2. The value of current which flows through each conductor of winding and the cross sectional area of each conductor depends upon the number of parallel path, number of series turn and number of conductor placed in width and height for each turn. The conductor width to height ratio is kept between 6.6 to 8.3 for both the redesign Ex e HV motors. The minimum conductor insulation thickness for both the motors is maintained 0.4mm. The separator (as shown in Figure 1) thickness is kept 4mm. The minimum radial insulation thickness of end windings and slot portion is provided 1.6mm and 1.4mm respectively. The detail of stator coil winding of redesign 970kW and 2200kW Ex e HV motor are shown in Fig. 1 and Table 1. The stator winding profile for both increased rotor mass and increased stator coil pitch is same. The insulation system of stator winding is tested and assessed successfully for voltage impulses and high voltage test in the 21% hydrogen in the air explosive gas mixture as per IS/IEC 60079-7 and it is ensured that insulation system of stator winding does not produce any arc or spark during starting or locked condition.

Table 1

Dimensions detail of stator coil profiles.

Motor rating	A1 (mm)	A2 (mm)	A3 (mm)	A4 (mm)	A5 (mm)	A6 (mm)
970 kW	4.5	2.4	80.9	74	9.6	10
2200 kW	4.5	2.4	111.9	105	18	18.4

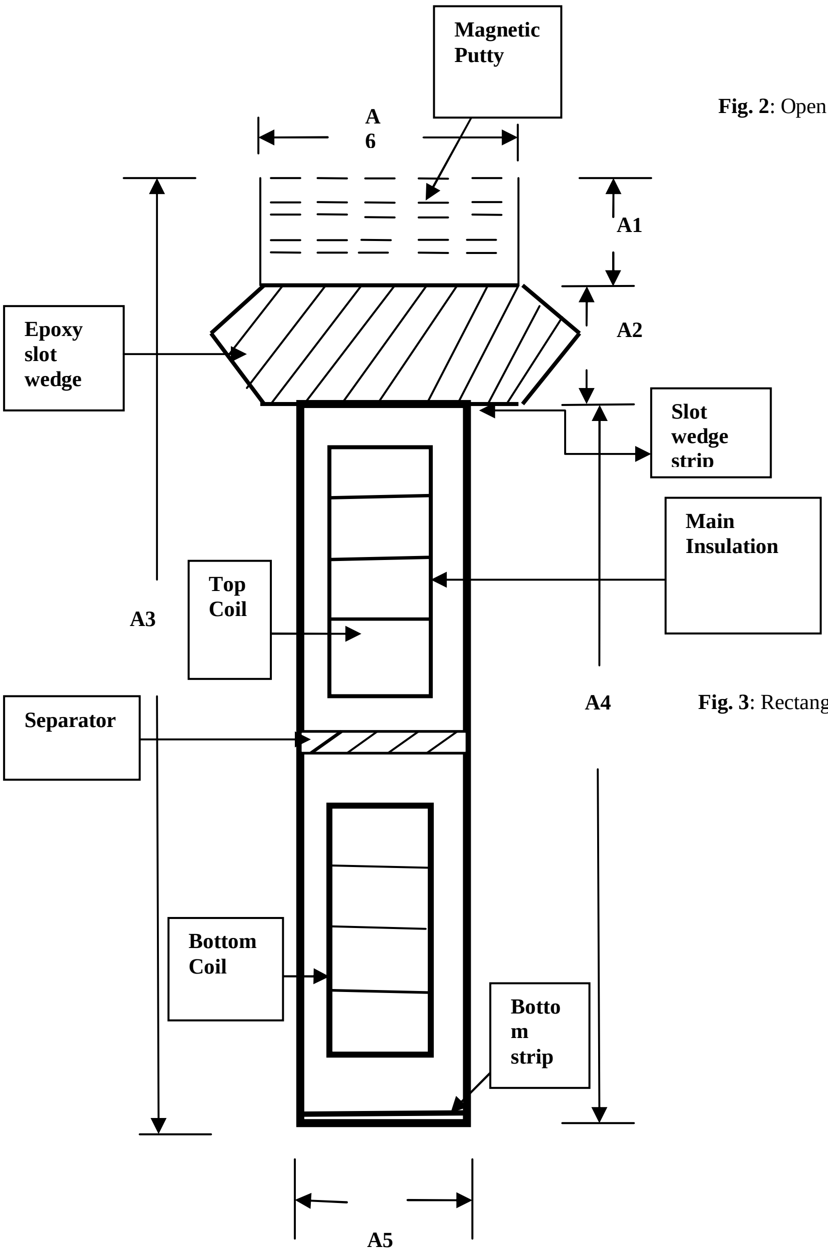


Fig. 1: View of stator coil profile for 970kW and 2200kW Ex e HV motor.

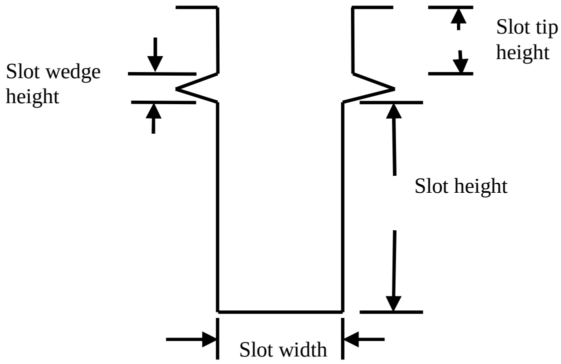


Fig. 2: Open type stator slot profile for 970 kW and 2200kW Ex e motors.

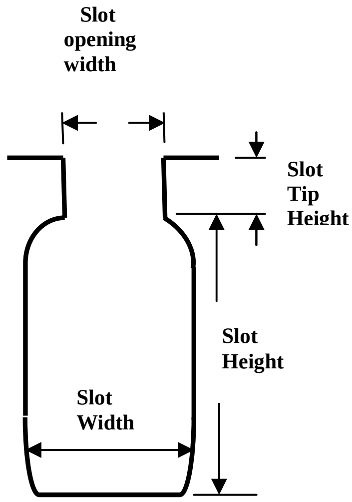


Fig. 3: Rectangular type rotor slot profile for 970kW Ex e motor

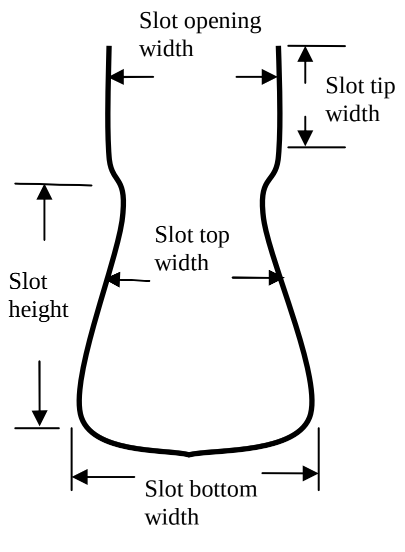


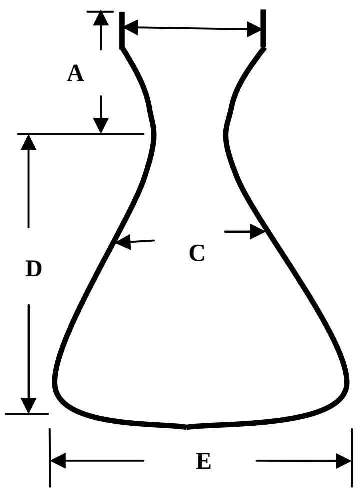
Fig. 4: Trapezoidal type rotor slot profile for 2200kW Ex e motor

3.2 Cage rotors

The bars of cage rotor are fitted tightly in the slots and then be brazed to the short-circuiting (SC) rings unless the bars and rings of the cages are manufactured as a single unit. The rotor slot profile for both the motors in all cases is shown in Fig. 3 and Fig. 4. The shape of rotor slot profile is rectangular and trapezoidal for low speed motor and high speed motor respectively. The rotor construction is assessed successfully for possible air gap sparking as per IS/IEC 60079-7. The limiting temperature (200°C) of the rotor is not exceeded, even during starting or blocked rotor condition by providing suitable current-dependent device to protect against exceeding the limiting temperature. The rotor outside diameter (Do) is calculated as Do= d-2lg, where d and lg are stator bore diameter and airgap length respectively.

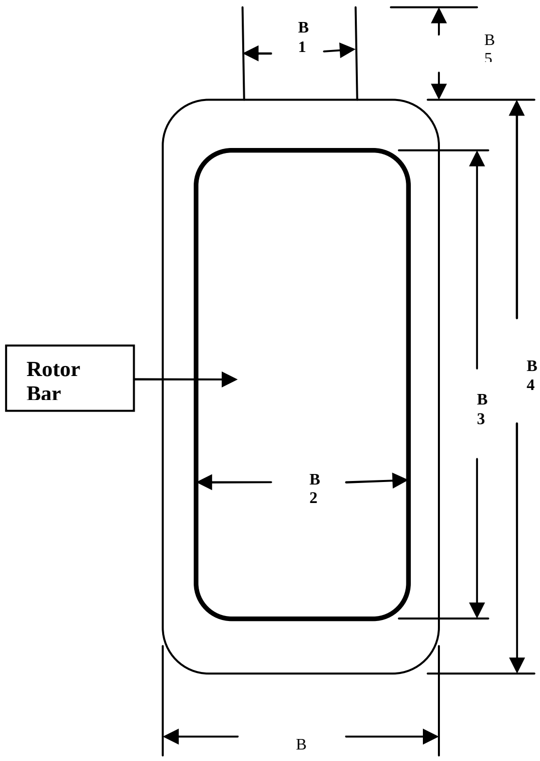
3.3 Rotor bar winding

The rotor bar has been used in the rotor core which is laminated with minimum thickness of 0.25mm class 'F' insulation class material. The rotor bars are inserted into the groove of the rotor. The length of rotor bar is kept higher than the rotor. The ends of bars are brazed for short circuiting with short circuit ring. The detail of rotor bar slot profile and rotor bar profile is shown in the Fig. 5 and Fig. 6. The shape of rotor bar is designed in rectangular shape for 970kW motor and trapezoidal shaped for 2200kW motor.



Motor rating	A	C	D	E	F
2200kW	4.5mm	6.5mm	60mm	13mm	4.5mm

Fig. 5: Trapezoidal Rotor bar profile for 2200kW Ex e HV motor.



Motor rating	B	B1	B2	B3	B4
970kW	6.5	2.5mm	6mm	39.4mm	40mm

Fig. 6: Rectangular Rotor bar profile for 970kW Ex e HV motor.

3.4 Air gap

The air gap between stator and rotor of motor is a very critical part which depends on the performance parameters of the motor like magnetizing current, power factor, overload capacity, cooling and noise. These performance parameters are affected by the length of air gap between stator and rotor. 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 air gap calculation for Ex e motor is done on the basis of equation (4).

Air gap(l_g) = {0.15+ [(Do-50)/780] [0.25+(0.75× n/1000)]} ry
(4) [2]

Where, Do = rotor diameter in mm (subject to a minimum of 75mm and a maximum of 750mm), r = core length/(1.75 × Do), n = maximum rated speed in RPM and y= 1 for motor with rolling bearing or 1.5 for plain bearing.

The rotor air gap was kept higher than the calculated value for Ex e motor. 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 all Ex e motors under discussion is calculated by using equation (4). The value of rotor diameter (Do) and core length are kept constant while designing the motor with increase in rotor mass and increase in stator coil pitch. The value of different design parameters are tabulated in the Table 2.

Table 2

Radial air gap design parameters of Ex e motors.

Motor rating	**Do 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
2200 kW	330	2970	862	1	1.49	1.545	5

3.5 Degrees of protection

The special enclosure is designed for these Ex e HV motors which compiles with IP 55 degrees of protection for weatherproofness as defined in IEC 60034-5 [15] and IS/IEC 60529-2001[16]. The motor enclosure and terminal enclosures are dust protected and water protected from jetting. The IP 55 ingress protection means that ingress of dust is not totally protected but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety.

3.6 Fasteners

Special fasteners according to IS/IEC 60079-0:2004 are used in Ex e HV motors for increasing the safety of hazardous area in which fasteners can be opened only by a special tools to avoid unauthorized openings.

3.7 Bearing seals and shaft seals

The rolling element bearings are used and the minimum radial or axial clearance between the stationary and rotating parts of seal is kept more than 0.05 mm as per requirement of IS/IEC 60079-7.

3.8 Space Heater

The certified flameproof (Exd) space heater is provided which is the requirement of increased safety HV motor to heat up the stator winding of Ex e motor, when heating is required. The minimum temperature of space heater is limited to 180ºC in any condition by providing a suitable temperature protective device.

4. Design parameters of Ex e motor

The Ex e motors of rating 970kW, 6.6kV, 18pole (low speed motor) and 2200kW, 6.6kV, 2 pole (high speed motor) were redesigned for higher time t_E of motors by using the two proposed methods. The methods as discussed earlier are as follows:

- by increasing the mass of rotor bar, and
- by increasing the stator coil pitch

When it is compared with the redesigned parameters with original designed parameters of 970kW and 2200kW motors and it is found that there are changes in design parameters from original parameters. Table 3 and Table 4 show the comparison of various parameters of redesigned motor with increase in rotor bar mass and stator coil pitch and normal Ex e motor of same ratings. It has been observed that the parameters of redesigned motor with increase in rotor bar mass and stator coil pitch are different their normal Ex e motor of same ratings.

Table 3

Change in design parameters with increase in rotor bar mass

Change in design Parameters for increase in rotor bar mass	**970kW,18pole,6.6kV Motor (low speed)**		**2200kW,2pole,6.6kV Motor (high speed)**	
	Normal motor	**Increase in rotor bar mass**	**Normal motor**	**Increase in rotor bar mass**
Rotor Total Slot Height (mm)	40	40	60	65
Rotor Slot Width (outer) (mm)	6.5	6.5	6.5	8.5
Rotor Slot Width (inner) (mm)	6.5	6.5	13	15
Magnetic stress during short circuit	0.089	0.094	0.415	0.434
Rotor phase current at reference temperature (A)	117.9	120.6	216.4	215.4
Current loading in stator (A)	45.6	46.6	62.5	62.2
Current density in stator winding (A/mm^2)	2.98	3.04	1.89	1.88
Rotor tooth size (mm)	Bottom=10.3 Middle=9.8 Top =9.3	Bottom=8.8 Middle=8.1 Top =7.5	Bottom=21.7 Middle=16 Top =10.3	Bottom=19.6 Middle=13.7 Top =7.9
Maximum air gap flux density (Tesla)	0.721	0.721	0.431	0.424
Magnetic field strength at stator tooth middle (AT/mm)	1.482	1.275	0.168	0.168
Magnetic field strength at rotor tooth middle (AT/mm)	1.221	5.255	0.315	2.112
Height of stator yoke (mm)	76	76.6	148.1	148.1
Height of rotor yoke (mm)	149	139	65.5	60.5
Width of copper bar of rotor (mm)	6	7.5	6	8
Height of copper bar of rotor (mm)	39.4	49.4	59.4	64.4
Mass of rotor bar (kg)	469.7	709.5	447.4	539

Table 4

Change in design parameters with Increase in stator coil pitch

Change in design Parameters with increase in stator coil pitch	970kW,18pole,6.6kV Motor (low speed) Normal motor	Increase in stator coil pitch	2200kW,2pole,6.6kV Motor (high speed) Normal motor	Increase in stator coil pitch
Coil pitch	7	8	20	22
Chording coil pitch	7/8	8/9	20/27	22/27
Winding factor of stator	0.945	0.956	0.877	0.915
Half of Mean length of turn in Stator (mm)	1459	1473	2180	2278
Total length of elementary Conductor (mm)	3781	3818	4708	4921
Single sided Axial winding overhang (mm)	235	240	446	472
Length ratio (Ratio of average length of winding overhang to Height of insulated)	8	8.2	13.3	14.3
Magnetic stress during short circuit	0.089	0.086	0.415	0.405
Total resistance of stator and Rotor winding at 20°C (mΩ)	838.42	846.68	181.65	189.85
Total resistance of stator and Rotor winding at 75°C (mΩ)	1020.68	1030.74	221.14	231.12
Per phase stator winding resistance at 75°C (mΩ)	340.23	343.58	73.71	77.04
Rotor phase current at reference temperature (A)	117.9	117.3	216.4	217.7
Current loading in stator (A)	45.6	46.3	62.5	62.9
Current density in stator winding/Rotor bar/SC ring (A/mm^2)	2.98	2.96	1.89	1.90
Maximum air gap flux density (Tesla)	0.721	0.712	0.431	0.413
Magnetic field strength at stator tooth middle (AT/mm)	1.482	1.361	0.168	0.161
Magnetic field strength at rotor tooth middle (AT/mm)	1.221	1.128	0.315	0.263
Height of copper bar of rotor (mm)	39.4	39.4	59.4	59.4
Stator winding cross sectional area (mm^2)	41.3	41.3	29.67	29.67
Stator winding mass (kg)	677.6	684.2	1212.2	1266.9

5. Comparison of performance in terms of increase in t_E

The Ex e HV induction motors are redesigned with increase in rotor bar mass and stator coil pitch and the parameters are tabulated in Table 5. All the motors are tested successfully for no load, locked rotor test, heat run test, ignition risk assessment (voltage impulse and high voltage test in explosive gas mixture) etc.[17]. After that some parameters are determined and important values of these performance parameters of redesigned Ex e motors and normal motors as shown in Table 5. A comparative study of the performance of low speed and high speed redesigned motors has also been done and the comparative performance analysis is given in Table 6. The studies denote that the temperature rise of stator windings of low speed motors decreases less than 0.35% in both the cases from normal motor. Similarly, temperature rise decreases to about 7.5% in increased rotor bar mass whereas about 7.18% increase in increased stator coil pitch method for high speed motors.

The performance analysis in case of time t_E of rotor of low speed motor increased to about 93.02% and 7.57% by increasing rotor bar mass of motor and stator coil pitch method respectively. Similarly, time t_E of rotor of high speed motor increased to about 33.02% and 4.77% by increasing rotor bar mass of motor and stator coil pitch method respectively. The result reveals that time t_E of rotor is higher in the increased rotor bar mass method for both low and high speed motors.

The changes in stator time t_E of low speed motor indicates that about 6.63% value of time t_E is decreased by increasing rotor bar mass of motor and about 9.25% t_E increased in case of stator coil pitch method. Similarly, time t_E of stator of high speed motor is decreased to about 3.15% by increasing rotor bar mass of motor and about 6.67% t_E increased in the stator coil pitch method. It is observed that time t_E of stator is higher in case of the increased stator coil pitch method for both low and high speed motors. The lowest value of t_E is considered as time t_E of Ex e motor for setting of protective devices.

The rotor bar mass is increased about 51% and 20.47% for low speed motor and high speed motor respectively in case of rotor bar mass increased method. The stator winding mass is increased less than 1% and 4.5% for low speed motor and high speed motor respectively in case of stator coil pitch method.

Table 5 Performance parameters of Ex ‘e’ motors.

Performance Parameters	970kW,18pole,6.6kV Motor (low speed)			2200kW,2pole,6.6kV Motor (high speed)		
	Normal Motor	**Rotor Mass increased**	**Increase in stator slot pitch**	**Normal Motor**	**Rotor Mass increased**	**Increase in stator slot pitch**
Temperature rise at full load (ºC)	44.13	43.98	44	64.99	60.11	69.66
Time t_E for stator (sec)	89.44	83.51	97.72	65.01	62.96	69.35
Time t_E for rotor (sec)	16.77	32.37	18.04	12.78	17	13.39
Time t_E for tripping device of Ex e motor (sec)	≤ 16.77	≤ 32.37	≤18.04	≤ 12.78	≤ 17	≤13.39
Stator current density (A/mm^2)	13.21	13.69	12.69	13.52	14.21	12.59
Efficiency at full load (%)	95.86	96.03	95.86	96.03	96.24	95.03
Pull out torque (p.u.)	2.388	2.378	2.288	1.834	1.903	1.716
Speed at Full load (rpm)	330.7	331.5	330.6	2969.9	2976.1	2966.8
Slip at Full load	0.00789	0.00536	0.00815	0.01003	0.00796	0.01107
Starting current (A)	545.7	565.7	524.5	401.3	421.9	373.8
Starting torque (p.u.)	1.076	0.995	1.006	0.593	0.537	0.566
Power factor at full load	0.739	0.721	0.742	0.919	0.921	0.919
Core losses at no load (kW)	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =10.86	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =10.93	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =10.60	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =6.83	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =6.83	Iron loss of stator tooth + Iron loss of stator yoke + Iron loss of rotor teeth + Pulsation loss in rotor =6.28
Stator copper losses at full load (kW)	14.66	15.34	14.65	10.53	10.43	11.13
Rotor copper losses at full load (kW)	8.0	5.42	8.26	23.06	18.27	25.48
Ratio Starting current/rated current (I_A/I_N)	4.23	3.53	4.06	2.22	2.34	2.07
Total Iron and Cu losses (kW)	33.52	31.69	33.51	40.42	35.53	42.89
Stator winding mass (kg)	677.6	677.6	684.2	1212.2	1212.2	1266.9
Rotor bar mass (kg)	469.7	709.5	469.7	447.4	539	447.4

Table 6

Performance analysis of Ex e induction motor.

Performance analysis in comparison with normal Ex e motors	970kW,18pole,6.6kV Motor (low speed)		2200kW,2pole,6.6kV Motor (high speed)	
	Rotor Mass increased	**Increase in stator slot pitch**	**Rotor Mass increased**	**Increase in stator slot pitch**
Temperature rise	0.34% decrease	0.29% decrease	7.50% decrease	7.18% increase
Increase of time t_E of rotor	93.02%	7.57%	33.02%	4.77%
Time t_E of stator	6.63% decrease	9.25% increase	3.15% decrease	6.67% increase
Current density	3.63% increase	4.09% decrease	5.10% increase	6.87% decrease
Efficiency at full load	0.17% increase	0%	0.21% increase	1.04% decrease
Starting current	3.60% increase	3.88% decrease	5.10% increase	6.85% decrease
Speed at full load	0.24% increase	0.03% decrease	0.20% increase	0.10% decrease
Slip at full load	0%	32.06% decrease	2.06% decrease	10.36% increase
Core losses at no load	0.64% increase	2.39% decrease	0%	8.05% decrease
Total core and copper Losses (Core losses at no load+ Stator copper losses at full load+ Rotor copper losses at full load)	5.45% decrease	0.02% increase	12.09 decrease	6.1% increase
Stator copper losses at full load	4.63% increase	0.06% decrease	0.94% decrease	5.69% increase
Rotor copper losses at full load	32.25% decrease	3.25% increase	20.77% decrease	10.49 increase
I_A/I_N ratio	16.5% decrease	4.01% decrease	5.40% increase	6.75% decrease
Decrease in starting torque	7.52%	6.50%	9.44%	4.55%
Increase in stator winding mass	0%	0.97%	0%	4.31%
Increase in Rotor winding mass	51.05%	0%	20.47%	0%

The time t_E and I_A/I_N ratio are the prime factors for the increased safety motors. The significant value of the I_A/I_N ratio is less than the normal motor in both the methods. The obtained results shows that the current ratio value is less in increased rotor bar mass method as compared to increase in stator coil pitch method for both the motors. The values of time t_E and I_A/I_N ratio are given in the Table 7. The I_A/I_N ratio value is less than 10 in all the cases and it should not be more than 10 for Ex e motor [2].

Table 7

I_A/I_N and Motor t_E of normal Ex e motor and Ex e motor with increase in stator coil pitch.

Safety parameters	970kW Motor rating			2200kW Motor rating		
	Normal Motor	**Rotor Mass increased**	**Increase in stator slot pitch**	**Normal Motor**	**Rotor Mass increased**	**Increase in stator slot pitch**
$t_{E,}$ (sec)	16.77	32.37	18.04	12.78	17	13.39
I_A/I_N	4.23	3.53	4.06	2.22	2.34	2.07

Table 8

Load, efficiency and power factor parameters of Ex e HV motors.

Load %	970kW Motor rating						2200kW Motor rating					
	Normal Motor		**Rotor Mass increased**		**Increase in stator slot pitch**		**Normal Motor**		**Rotor Mass increased**		**Increase in stator slot pitch**	
	η (%)	**p.f.**	**η (%)**	**p.f.**	**η (%)**	**p.f.**	**η (%)**	**p.f.**	**η (%)**	**p.f.**	**η (%)**	**p.f.**
25	91.9	0.333	91.7	0.314	92.12	0.341	91.83	0.87	91.86	0.862	91.90	0.887
50	95	0.553	95.06	0.529	95.17	0.563	95.09	0.93	95.18	0.927	95.09	0.934
75	95.81	0.676	95.89	0.654	95.84	0.683	95.91	0.932	96.05	0.932	95.86	0.932
100	95.86	0.739	96.03	0.721	95.86	0.742	96.03	0.919	96.24	0.921	95.93	0.914
125	95.88	0.706	96	0.686	95.90	0.712	95.79	0.892	96.08	0.898	95.59	0.881

The efficiency and power factor values are specified at various load 25, 50, 75, 100 and 125 percentages in the Table 8. The efficiency and power factor of all the motors increases as load increased in all the cases. The efficiency in both the cases (increase in rotor bar mass and increase in stator coil pitch) is more or less same as compared to normal Ex e motors. The efficiency and power factor at 75% load remain almost constant in both the cases for low and high speed motor. At 100% load, the efficiency increases in case of rotor mass increased method for both the speed of motors as compared to increase stator slot pitch method but power factor is decreased reasonable.

6. Conclusion

The study reveals that the time t_E increases significantly in both the cases for both the motors. It is observed that the value of time is higher in case of increased rotor bar mass method as compared to increase in stator coil pitch method. About 93% time t_E has increased by increasing about 51% rotor bar mass in increase rotor bar mass method for low speed motor whereas, about 33% time t_E has increased by increasing about 20% rotor bar mass for high speed motor. The time t_E has enhanced 9.25% and 6.67% for 970kW and 2200kW Ex e motors respectively in case of stator coil pitch method. It is concluded that these two proposed methods can be suitable for increasing the time t_E of the increased safety motor for hazardous areas. The price of the motor can be increased in the case of rotor bar mass method due to increase in quantity of copper bars but safety is increasing so with respect to the safety aspect of motor as well as installation of hazardous areas, price can be compromised. The performance of the redesigned Ex e HV motor has achieved the requirement of the end user. The design aspect of squirrel cage induction motor has been described for increased safety motors in this paper. As temperature rise of the motor would be limited and less then the ignition temperature of the surrounding explosive atmosphere because of switching off of power supply by the current-dependent protective relay/device before time t_E has elapsed. The motor operation in hazardous area would be more safe. The above designed Ex e HV motors are operating successfully at the different locations of oil sectors in India.

Acknowledgement

The authors are grateful to Dr. P. K. Singh, Director, CSIR-CIMFR, Dhanbad for his kind permission to publish this technical research paper and also wish to record thanks to the Dr. A. K. Singh, Head of Flameproof & Equipment Safety Lab., CIMFR, Mr. S. R. Prasad, Former Executive Director, BHEL, Mr. G. P. Baghel, Assistant General Manager, Mr. N. Khare, Assistant General Manager, BHEL, Mr. B. Jena, Manager, BHEL, Bhopal for providing necessary help in carrying out this research work.

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