Some methods to increase the time t_E of increased safety Ex e motor for explosive atmospheres

Dr. Bhagirath Ahirwa and Dr. Tarun Kumar Chatterjee

Abstract— **Increased safety (Ex e) High Tension (HT) squirrel cage induction motors are being designed for safe operation in the explosive atmospheres. 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 specified abnormal condition in hazardous area. The research work shows that the time t_E of Ex e motor can be increased by two proposed methods; by increasing the mass of rotor bar or by increasing the stator coil pitch. Low speed and a high speed HT 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 HT motor designers.**

***Index Terms*—Increased safety motor, time t_E, I_A/I_N, temperature rise.**

I. 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 as specified in IS/IEC 60079-7 [2]. 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 [4, 5]. 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 [3 - 4]. 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 HT motor shall be designed to assess for permissible breakdown impulse voltage in explosive gas mixture without failure of stator winding [11].

The t_E and I_A/I_N ratio are very important parameter for Ex e motor. I_A/I_N ratio is the ratio of starting current to rated current of Ex e motor and it should not be more than 10 [2]. 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 HT 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 HT induction motor The objectives of this paper are;

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 tE, temperature rise and performance of motor.

The Ex e three phase HT 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 for study and the same motors are redesigned with increase in

Manuscript received October 10, 2014.

Dr. Bhagirath Ahirwal, Flame & Explosion Lab., CSIR-Central Institute of Mining and Fuel Research, Dhanbad, India, +91-9431158946.

Tarun Kumar Chatterjee, Electrical Engineering Department, Indian School of Mines, Dhanbad, India, +91-9431122651.

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.

II. Methodology of Design of Ex E motor

As we know that heat balance equation is

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

So equation (1) can be written as

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

and it is known that I2R = Starting torque × kW rating of motor, so by putting the value of I2R in equation (2)

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

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 (Ahirwal & Chatterjee formula; for time t_E with respect to starting torque) i.e. time tE 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.

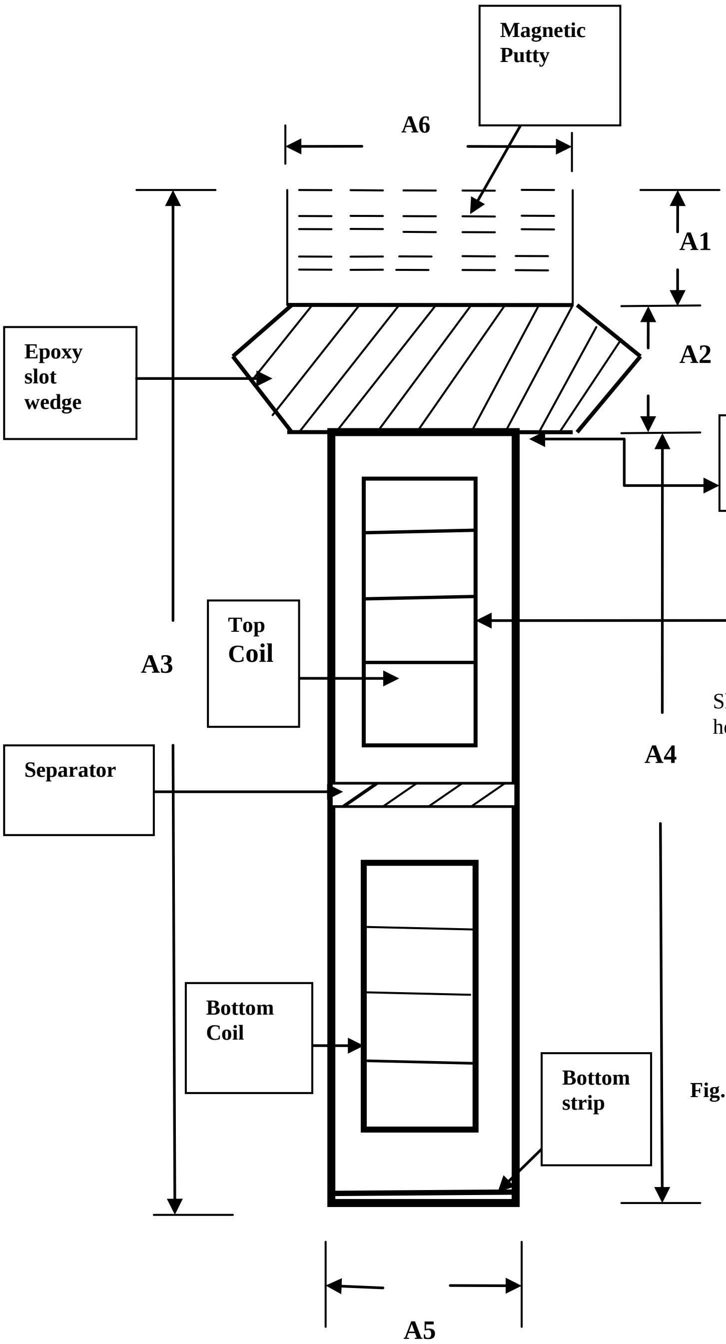
Similarly , in the same manner if s, $\Delta\Theta$ and b are constant for particular motor design in the above equation (2) so it can be written as $t_E \propto m/I^2R$ (Ahirwal & Chatterjee formula; for time t_E with respect to rotor copper loss) i.e. time t_E is proportional to the mass of rotor winding 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.

III. Important Design parameters of Ex e HT motor

A. 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 enameled. 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 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 is 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/mm2. The designed current density of stator winding in the designed motor is between 1.88 and 3.04 A/mm2. 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 HT 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 HT 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.



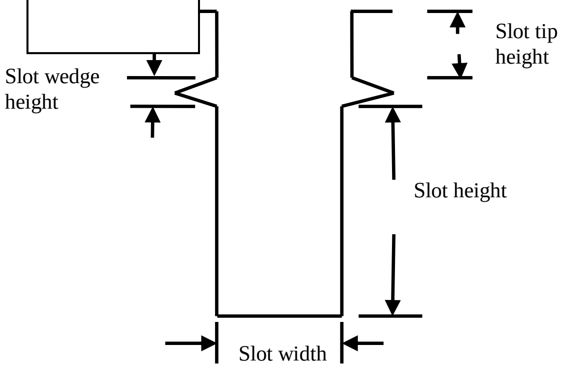
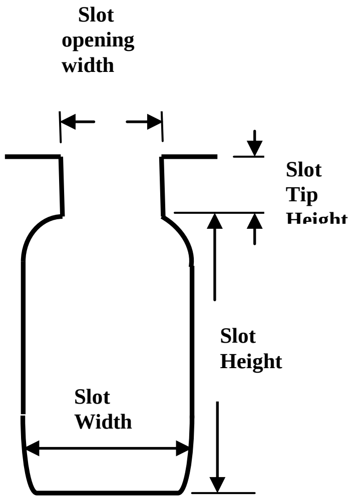


Fig. 2: Open type stator slot profile for 970 kW and 2200kW Ex e motors.

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

Table 1. Dimensions detail of stator coil profiles.

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



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

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

B. Cage Rotors

The bars of cage rotor is 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.

C. 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.
Helpful Hints

D. 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).

$$\text{Air gap}(l_g) = \{0.15+ [(Do-50)/780]\,[0.25+(0.75\times n/1000)]\}\, ry \quad [2] \qquad (4)$$

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.

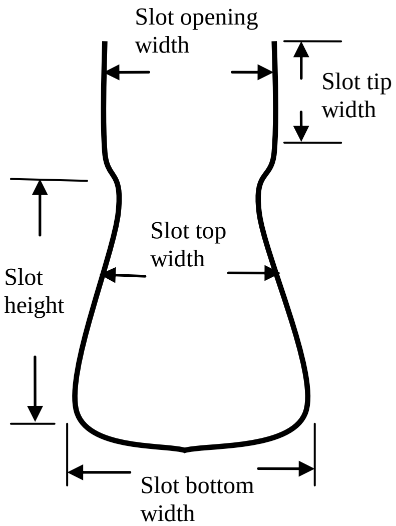
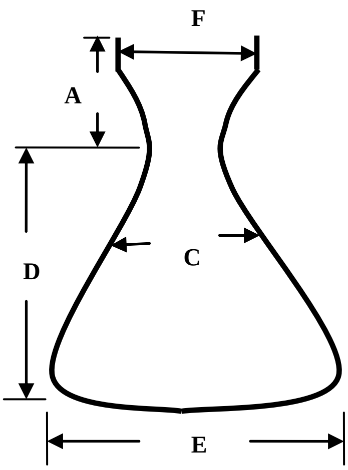
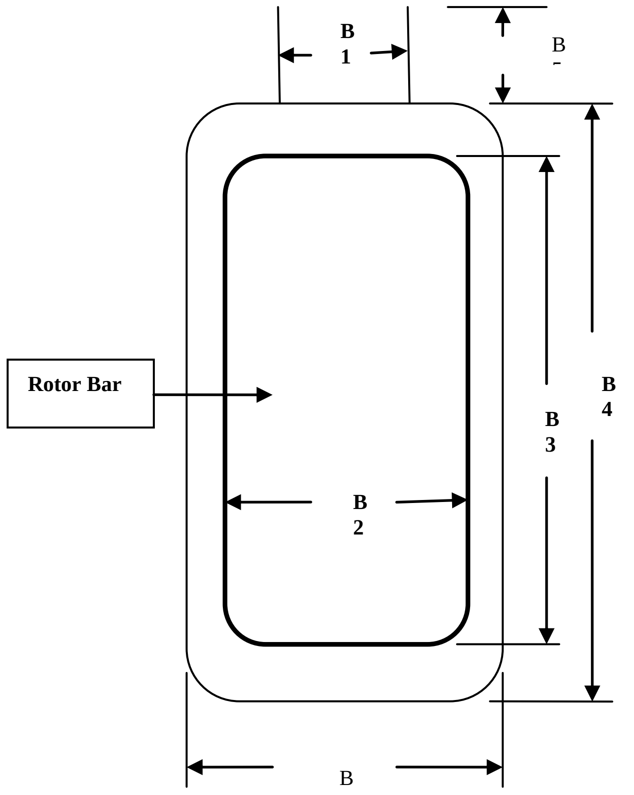


Fig. 4: Trapezoidal type rotor slot profile for 2200kW Ex e motor.



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 HT motor.



Motor rating	B	B1	B2	B3	B4	B5
970kW	6.5mm	2.5mm	6mm	39.4mm	40mm	1mm

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

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	1.490	1.545	5

IV. 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) are 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 in mm	40	40	60	65
Rotor Slot Width (outer) in mm	6.5	6.5	6.5	8.5
Rotor Slot Width (inner) in 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 in Amp	117.9	120.6	216.4	215.4
Current loading in stator in Amp	45.6	46.6	62.5	62.2
Current density in stator winding in A/mm2	2.98	3.04	1.89	1.88
Rotor tooth size in 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 in Tesla	0.721	0.721	0.431	0.424
Magnetic field strength at stator tooth middle in AT/m	1.482	1.275	0.168	0.168
Magnetic field strength at rotor tooth middle in AT/m	1.221	5.255	0.315	2.112

Height of stator yoke in mm	76	76.6	148.1	148.1
Height of rotor yoke in mm	149	139	65.5	60.5
Width of copper bar of rotor in mm	6	7.5	6	8
Height of copper bar of rotor in mm	39.4	49.4	59.4	64.4
Mass of rotor bar in 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)		2200kW,2pole,6.6kV Motor (high speed)	
	Normal motor	Increase in stator coil pitch	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 in mm	1459	1473	2180	2278
Total length of elementary Conductor in mm	3781	3818	4708	4921
Single sided Axial winding overhang in 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 in mΩ	838.42	846.68	181.65	189.85
Total resistance of stator and Rotor winding at 75°C in mΩ	1020.68	1030.74	221.14	231.12
Per phase stator winding resistance at 75 °C in mΩ	340.23	343.58	73.71	77.04
Rotor phase current at reference temperature in Amp	117.9	117.3	216.4	217.7
Current loading in stator in Amp	45.6	46.3	62.5	62.9
Current density in stator winding/Rotor bar/SC ring in A/mm^2	2.98	2.96	1.89	1.90
Maximum air gap flux density in Tesla	0.721	0.712	0.431	0.413
Magnetic field strength at stator tooth middle in AT/m	1.482	1.361	0.168	0.161
Magnetic field strength at rotor tooth middle in AT/m	1.221	1.128	0.315	0.263
Height of copper bar of rotor in mm	39.4	39.4	59.4	59.4
Stator winding cross sectional area in mm^2	41.3	41.3	29.67	29.67
Stator winding mass in kg	677.6	684.2	1212.2	1266.9

V. Comparison of Performance in Terms of Increase

The Ex e HT 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.

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].

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.

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, second	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 HT 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	33.3	91.7	31.4	92.12	34.1	91.83	87	91.86	86.2	91.90	88.7
50	95	55.3	95.06	52.9	95.17	56.3	95.09	93	95.18	92.7	95.09	93.4
75	95.81	67.6	95.89	65.4	95.84	68.3	95.91	93.2	96.05	93.2	95.86	93.2
100	95.86	73.9	96.03	72.1	95.86	74.2	96.03	91.9	96.24	92.1	95.93	91.4
125	95.88	70.6	96	68.6	95.90	71.2	95.79	89.2	96.08	89.8	95.59	88.1

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 , °C	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	10.86	10.93	10.60	6.83	6.83	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	**970kW,18pole,6.6kV Motor (low speed)**	**2200kW,2pole,6.6kV Motor (high speed)**

motors	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%

CONCLUSION

The study reveals that the time t_E increases significantly in both the proposed methods 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. The time t_E and I_A/I_N ratio of both the redesigned motor is considerably fulfill the requirement of the IS/IEC 60079-6:2006 standards for both the proposed methods. 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 HT motor has achieved with the requirement of the end user. The above designed Ex e HT motors are operating successfully at the different locations of oil sectors in India.

ACKNOWLEDGMENT

The authors are grateful to Dr. Amalendu Sinha, 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 Flame & Explosion Lab., CIMFR, Mr. S. R. Prasad, Executive Director, BHEL, Mr. G. P. Baghel, Deputy General Manager, Mr. N. Khare, Deputy General Manager, BHEL, Mr. B. Jena, Deputy Manager, BHEL, Bhopal for providing necessary help in carrying out this research work.

REFERENCES

[1] IS 5571 (2009) Guide for selection and installation of electrical equipment in hazardous area (other than mines). Bureau of Indian Standards (BIS).
[2] IS/IEC 60079-7 (2006) Electrical apparatus for explosive gas atmospheres- Increased safety. Bureau of Indian Standards (BIS).
[3] J. Bredthauer, L. B. McClung and Tretzack H. (2002) Risk of Ignition due to Transition Currents in Medium Voltage Motors for Classified Locations. IEEE Transactions on Industry Application: 27(6),1195-1203.
[4] J. Bredthauer and N. Struck (1995) Starting of Large Medium Voltage Motor: Design, Protection and Safety Aspects. IEEE Transactions on Industry Application: 31(5):1167-1176.
[5] J.H. Dymond, N. Stranges, K. Younsi and J. E. Hayward (2002) Stator Winding Failures: Contamination, Surface Discharge and Tracking. IEEE Transactions on Industry Application: 38 (2), 577-582.
[6] R. Ong, J. H. Dymond, and B. Mistry (2002) Design of increased safety electrical machine: Development activities and certification testing. IEEE PCIC Conference: 65–75.
[7] P. Clark, G. Neville, and R. Regan (1996) Solutions for MV motors and generators in hazardous locations. International Conference PCIC-96: 61–73.
[8] K. Padden, Rick Bried and James H. Dymond Lorraine (2005) Instructional overview of IEEE 1349-2001—Guide for the Application of Electric Motors in Class I, Division 2 Hazardous (Classified) Locations. IEEE Transactions on Industry Applications: 41 (1), 101-111.
[9] Jussi Rautee, Frank Lienesch and Tom Liew (2008) Safety improvements of non-sparking and increased safety motors. Fifth IEEE PCIC-Electrical and Instrumentation Application: 1-9.
[10] Dirk Arnold and Vladimir Barinberg (2008) Explosion protected electrical machines with type of protection "e" and "nA" Requirements, Risk Analysis, Type tests, Conclusions. Proceedings of the IEEE 2008 International Conference on Electrical Machines: 1-4.
[11] Hee-Dong Kim, Tae-Sik Kong (2012) Assessment of insulation deterioration in stator winding of high voltage motor. The transactions of the Korean Institute of Electrical Engineers: 61 (5), 711-716.
[12] B. Ahirwal, A. K. Singh, R. K. Vishwakarma, A. Sinha (2009) Increased Safety Protection and Energy Conservation for Motors installed in Zone 1 & 2 Hazardous area using variable Speed drives (VSDs). International Journal of COMADEM: 12 (1), 15-23.
[13] Wei Cong, Lu Xuezhong, Liu Xiaosheng, Li Hongyan, Tian Guoqun, Zhou Sheng (2012). Study of Impulse stress gradient on stator winding of HV explosion-proof motor. IEEE 10th International conference on the Properties and Applications of Dielectric Materials: 1-8.
[14] IS/IEC 60079-0 (2004) Electrical apparatus for explosive gas atmospheres-General requirements. Bureau of Indian Standards (BIS).
[15] IEC 60034-5 (2006) Rotating electrical machines – Part 5: Degrees of protection provided by the integral design of rotating electrical

machines (IP code) – Classification. International Electrotechnical commission.
[16] IS/IEC 60529 (2001) Degree of protection provided by enclosure (IP CODE). Bureau of Indian Standards (BIS).
[17] Bhagirath Ahirwal, T. K. Chatterjee, A. K. Singh (2011) Assessment and control of ignition risk of HT induction motor for increased safety Ex ‘e’ as per Indian standard for explosive atmospheres. IEEE PSES, USA: 1-5.

Dr. Bhagirath Ahirwal is graduated in Electrical Engineering from the Indira Gandhi Government Engineering College, Sagar in 1996 and PhD in Electrical Engineering from Indian School of Mines, Dhanbad. He has employed in the IREL under Deptt. of Atomic Energy, Govt. of India, as an Electrical Engineer and responsible for electrical maintenance of Boiler Plant, 132/11KV power receiving station and machines drives from 1997 to 2002. Since 2002 he is a Scientist and actively involved in the R&D, Design Evaluation and Certification of Ex e motor and other Ex equipment for hazardous areas in the Flame & Explosion Laboratory, CSIR-Central Institute of Mining and Fuel Research. He is also a Member of Electrical Apparatus for Explosive Atmospheres Sectional Committee, ET-22 of Bureau of Indian Standards and Member of National Committee for “Formulation on Selection, Installation and Maintenance of Electrical and Electronic Equipment for Coal Mines” constituted by DGMS, Govt. of India. He has been published more than 38 papers in the International and national journal of repute.

Dr. T. K. Chatterjee has about 29 years of teaching and research experience in Indian School of Mines, Dhanbad, India. Before joining teaching profession, he served in TATA STEEL for five years. He was the coordinator for modernization of Electrical Engineering Laboratories in the Department. Dr. Chatterjee participated in a number of R&D projects and was the investigator of UGC funded SAP project “On-line conditioning monitoring of heavy duty mine electrical drives”. He also successfully completed a few consultancy projects like “Performance of Main Mine Ventilation Fan” and “Assessment of Safety Circuits for 176 kW friction winder”. He also delivered lectures in various in-campus and off-campus short-term courses on Mine Electrical Engineering. Dr. Chatterjee underwent three months training on Longwall Electrical System in U.K. under British Council Fellowship. His specialization is Mine Electrical Engg., Electrical machines design & Drives.