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Refurbishment of a Three-Phase Induction Motor Reflecting Local Voltage Condition

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Abstract: *A 2.2-kW, 3-phase, 50Hz squirrel-cage induction motor originally designed for 415V(a.c.) application got burnt out from sustained thermal overload. Being that the local supply voltage hardly rises above 380V (a.c.), it had to be refurbished from first principles to reflect this voltage condition. The calculations leading to the choice of the number of poles, number of coils per phase per pole, number of phase groups, number of turns-in-series per phase, amongst other quantities, necessary for the realization of a 380V(a.c.) double-layer lap-type 3-phase stator winding with a diamond overhang were carried out. The method of direct-on-line starting was used to check the workshop performance of the machine. The value of the motor no-load speed was quite satisfactory. It is, however, emphatically recommended that a suitable under-voltage relay-protection scheme be incorporated in the motor power supply system to forestall such breakdown in future.*
Keywords: *Induction Motor, Refurbishment, Local Voltage Condition.*

I. Introduction

The induction motor as an electromechanical rotating equipment has been of great significance to industrialists since it came into existence in 1833[Say & Taylor, 1980]. For instance, the motor in question was used to drive a grinding tool in an electrical workshop. But having been left to run under a low voltage supply condition overnight, it became seriously overheated and got burnt as a result. In refurbishing the motor, it was considered necessary to adopt winding parameters relative to 380V (a.c.) which was the maximum local supply voltage level; whereas, the motor name-plate voltage specification was 415V(a.c.). Therefore, in Section 3.0 the machine calculations to that effect are presented, being preceded by the motor measurement details in Section 2.0. Section 4.0 deals with the refurbishment work proper. Section 5.0 provides details of the machine test results; whilst, conclusion and recommendations constitute the terminal part of this paper in Section 6.0.

II. Motor Measurement Details

First principle approach to cage motor stator refurbishment often involves measurement of the stator axial length and bore diameter, together with the slot, tooth and core dimensions. Essential measurements are also normally taken on the rotor. Of course, these measurements usually precede the actual machine calculations and the details are given below in Table 2.1.

Table 2.1: Values obtained from Essential Measurements of the Motor Stator and Rotor.

ITEM	VALUE	ITEM	VALUE
i) Stator Bore Diameter (D)	92mm	v) Rotor Bar Spacing (or slot pitch)	
ii) Effective Axial Length (L)	98mm	vi) Skew of Bars	9.5mm
iii) Number of Stator Slots (S)	36	vii) Effective Rotor Axial	9.5mm
iv) Number of Rotor Bars	32	Length	98mm

N.B: (i) Source: Form direct measurement and inspection of the motor.
(ii) Other Dimensions are as shown in Fig. 2.1 below

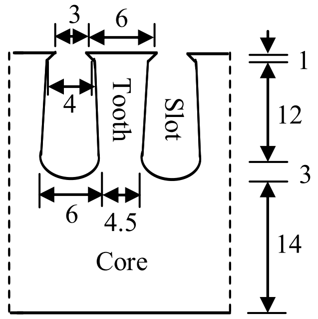

Fig.2.1 Dimensions of Slot, Tooth and Core *(All Measurements in mm and N.T.S.).*

III. Machine Calculations

3.1Choice of No. of Poles (2p):

The synchronous speed, N_s, of a motor is given by

$$N_s = 120f/2p = N_r/(1-s) \qquad \text{.....................................(3.1)}$$

Where p – pole pairs; N_r – rotor speed; s = slip. Thus, with N_r = 1420 rpm (from name-plate), and applying a slip of 5% which is the standard value for most practical machines according to [Say, 1976], we obtain the synchronous speed from (3.1) as

$$N_s = 1420/(1-0.05) = 1495\,rpm$$

or the *preferred value* of <u>1500 rpm</u> as in [Say, 1983]. Hence, the number of poles becomes

$$2p = \frac{120f}{N_s} = \frac{120x50}{1500} = 4(exactly).$$

3.2 Slot Pitch (λ):

For stator slots, S = 36 we shall have, *in terms of angle*, the slot pitch given by

$$\lambda = \frac{180(2p)}{S} = \frac{180x4}{36} = 20^o\ elect \qquad \text{..............................(3.2)}$$

3.3 No. of Coils (or Slots) per Pole per Phase (q):

The number of coils (or slots) per pole per phase is given by

$$q = S/2pm = 36/(4x3) = 3 \qquad \text{.. (3.3)}$$

This is OK since 'q' should be *at least* 3 to avoid excessive reactance [Say, 1983].

3.4 Pole Pitch (τ):

In electrical degrees, we have

$$\tau = 180^o\ (i.e.\ \pi\, rad.)\ elect. = (180/20)\lambda = 9\lambda \qquad \text{............... (3.4)}$$

3.5 Coil Pitch (γ) /Relative Chording Factor (β):

Machine coil pitches in practice usually fall between (⅔)τ and τ [Say, 1976]; implying that relative chording factors will fall between ⅔ and 1, exclusively. Hence, for a pole pitch, τ = 9λ, the coil pitch should be either (7/9) τ or (8/9) τ (meaning a relative chording factor of either (7/9) or (8/9). We shall select (8/9) for the motor, since chording equally reduces phase e.m.f.'s. Therefore, the motor coil pitch shall be

$$\gamma = \beta\tau = (8/9)\tau = 8\lambda = 160^o\ elect. \qquad \text{.............................. (3.5)}$$

Fortunately, the skewed cage rotor slots shall also help to suppress those high-order harmonics whose influence cannot be suppressed by the choice of relative chording factor, β [Liwschitz-Garik & Whipple].

3.6 Pitch Factor (K_{pn}):

Generally, the coil pitch factor for the nth harmonic is given by

$$K_{pn} = \sin\frac{n\beta\pi}{2} = \sin\frac{n\gamma}{2} \quad \text{[Chalmers, 1965]} \qquad \text{................ (3.6)}$$

Thus, fundamentally we have

$$K_{p1} = \sin\frac{(8/9)\pi}{2} = 0.985$$

3.7 Phase–Spread Angle (σ)/Winding Layer Method:

For a high-order distribution factor, the spread angle σ = 60° (elect.) shall be chosen. *A double-layer winding design has a lower leakage reactance and produces a better phase e.m.f. waveform than the corresponding single-layer winding design* [Daniels, 1976]. Thus, a double-layer (i.e."basket") winding method shall be adopted.

3.8 No. of Phase-group Coils (Θ):

This is given by

$$\Theta = p(2\pi)/\sigma = 360p/\sigma \qquad \text{.................................... (3.7)}$$
$$= 2x360/60 = 12$$

3.9 Distribution Factor (K_{dn}):

Usually, for an integral-slot winding (such as the design in question), the distribution factor is calculated from the equation involving harmonics given as

$$K_{dn} = \frac{\sin 0.5(n\sigma)}{q \sin 0.5(n\sigma/q)}$$ [Say, 1976] ……………………… (3.8)

Hence, the fundamental distribution factor is,

$$K_{d1} = \frac{\sin 0.5(1x60)}{3 \sin 0.5(1x60/3)} = 0.96$$

3.10 Winding Factor (K_{wn}):

$K_{wn} = K_{dn} . K_{pn}$ …………………………………(3.9)

Thus, for an integral-slot winding design, the fundamental winding factor is

$K_{w1} = K_{d1}.K_{p1}$ = 0.96 x 0.985 = 0.946

3.11 Specific Magnetic Loading ($B_{av.}$):

The stability and dynamic conditions of induction machines are highly affected by saturation [Okoro, 2003]. Thus, the choice of $\mathbf{B_{av}}$ is usually between 3 and 6Tesla [Singh, 1982]. We shall assume $\mathbf{B_{av}}$ ***= 0.49Tesla***.

3.12 Flux per Pole (Φ_p):

$$\Phi_p = (\pi DL/2p)B_{av}$$
$$= (\pi\, x 0.092 x 0.098/2 x 2) x 0.49 = 0.00347 Wb$$ …….(3.10)

3.14 Total No. of Turns (N), Total No. of Conductors (Z)
& No. of Conductors per Slot (Z′):

$N = 3N_{ph}$; $Z = 2N$; $N_{ph} = \frac{E_{ph}}{4\Phi_p f_b f K_{w1}}$ ……………………(3.11)

where $f_b = 1.11 \, and \, f = 50Hz$; [Kuale, 2003].

$$N_{ph} = \frac{380}{4x0.00347x1.11x50x0.946} = 521;$$ N = 3x521 =1563;

Z = 2x1563 = 3126; therefore, Z' = 3120/36 = 86.83

Since the value of Z' must be exactly divisible by 2 to give layers of equal number of conductors, we shall take Z' = 88. Consequently, we have

Z = 88x36 = 3168 and ***N_{ph} = 3168/2x3 = 528***

3.15 No. of Conductors per Layer(Z'') / No. of Turns per Coil (N_c):

$Z'' = Z'/2 = N_c$ = 88/2 = 44

3.16 Size of Conductor (S. W. G.):

By inspection of Fig.2.1 the approximate area of slot (or gross area), A_{sg}, is

$$A_{sg} = \frac{1x(3+4.8)}{2} + \frac{12(4.8+6.5)}{2} + \frac{\pi 3^2}{2} = 86\, mm^2$$

$= A_c/SF = Z'.a_c/SF$ …………………………………(3.12)

where A_c − Cross-sectional area of Total Conductors per Slot.

$a_c = \pi(d_c^{\,2})/4$, *cross-sectional area of each conductor.*

SF − Space Factor {0.25 to 0.4} [Agarwal, 2000].

Thus, applying SF = 0.25, we have conductor diameter as

$d_c = (4x0.25x86/88\pi)^{½} = 0.5577$ *or 0.56 mm;*

Whereby we select copper wire of ***S.W.G. 24*** as in standard workshop S.W.G. Tables.

3.17 No. of Wires in Hand:

Obviously, one (1) wire in hand of 44-conductor coil per layer is OK

3.18 Winding Formation:

The lap winding formation is the most common in practice and shall be used here.

3.19 Slot Allocation to Phase-Group Coil Sides as Designed.

Table 3.1 Slot Allocation to Phase-Group Coil Sides.

PHASE GROUP COIL No.	SPREADING OF PHASE GROUP COILS		PHASE GROUP COIL SIDES / SLOT NUMBERING		PHASE GROUP COIL FREE ENDS	
	POLE ASPECT	SEQUENCE AND POLARITY	BEGINNING COIL SIDES	ENDING COIL SIDES	START (s)	FINISH (f)
1		A1	1 2 3	***9 10 11***	(1)	***(11)***
2	NORTH	–C4	4 5 6	***12 13 14***	(4)	***(14)***
3		B1	7 8 9	***15 16 17***	(7)	***(17)***

4		–A2	10 11 12	***18 19 20***	(10)	***(20)***
5	SOUTH	C1	13 14 15	***21 22 23***	(13)	***(23)***
6		–B2	16 17 18	***24 25 26***	(16)	***(26)***
7		A3	19 20 21	***27 28 29***	(19)	***(29)***
8	NORTH	–C2	22 23 24	***30 31 32***	(22)	***(32)***
9		B3	25 26 27	***33 34 35***	(25)	***(35)***
10		–A4	28 29 30	***36 1 2***	(28)	***(2)***
11	SOUTH	C3	31 32 33	***3 4 5***	(31)	***(5)***
12		–B4	34 35 36	***6 7 8***	(34)	***(8)***

N.B.: (i) Ending/Lower Layer Coil Sides and 'Finish' Coil Sides are Italicized and emboldened; (ii) the sign (−) indicates negative polarity (elect.); (iii) ***Source:*** Allocation based on the foregoing design data.

3.20 The Schematic Winding Diagram:
The schematic winding diagram is as shown in Fig.3.1.

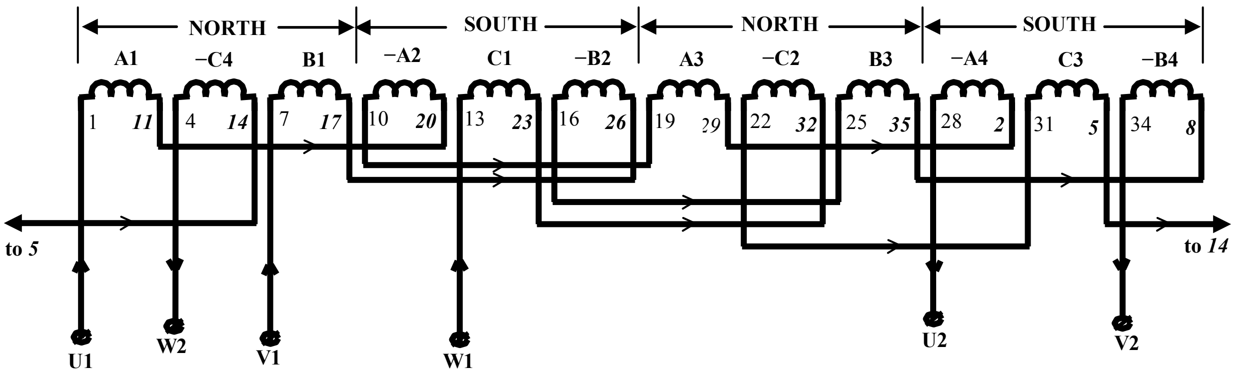

Fig.3.1: Schematic Winding Diagram Showing the 12 Phase-group Coils and their Arrangement under the 4 Poles and their Connection Pattern (i.e. Series/Series Connection).

IV. Refurbishment Work Proper

4.1 Rewinding of Stator

4.1.1 Preparation of Slots:

A strip of slot liner or ***latheroid*** was used to cover the entire inner surfaces of the slots and made to shoot out of the slot up to 10mm at least [Atabekov, 1980].

4.1.2 Coil Production:

A simple winding former was prepared with a plywood board and used to produce the required 72x186mm phase-belt coils of 44 turns per coil, leaving the free-end wire lengths up to 250mm. Next, each phase coil in a given phase group was duly separated with masking tape wrappings. A total of 12 phase groups were produced as per design.

4.1.3 Coil Insertion into Slots & Arrangement:

As the machine stator is the open-slot type, each of the 12 phase group coils was carried into the slot area making sure that the free-end wires were on the connection side of the machine. The winding layout of Table 3.1 was skillfully followed in putting the coils into the slots and having them properly arranged. Thereafter, a slot wedge made of dry *bambow* wood was used to secure the coils in each slot. The overhang portions of the phase-group coils were adequately insulated from each other with glass-fibre cloth-tape.

4.1.4 Coil Lead Connections/Pre-Impregnation Tests:

a) Coil Lead Connections:

The twelve (12) phase-group coils gave rise to 24 No. coil leads. The 4 phase-group coils of phase A (i.e. A1, –A2, A3 and –A4) were connected in series opposite formation to constitute one single circuit as in Fig.4.1

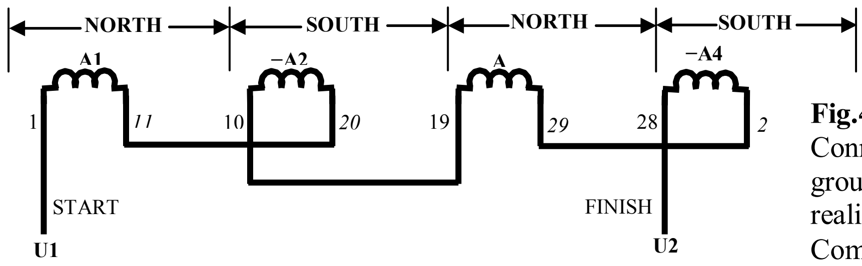

Fig.4.1: Series-Opposite Connection of the 4 Phase-group coils of Phase A to realize a Composite and Complete Phase Winding.

Phases B and C were each connected in the same manner forming altogether 3 ***composite phase windings*** with 6 terminal leads, (the "start" leads being 1or (U1), 7 or (V1) and 13 or (W1); the "finish" leads being 28 or (U2), 34 or (V2) and 4 or (W2), as shown in Fig.3.1.

b) Pre-Impregnation Workshop Tests:

Insulation resistance test was carried out and 5.4MΩ was got as the least value for phase-to-earth; 75MΩ (least value) for phase-to-phase measurements. This was OK for a 1-minute test with 500V(d.c.) @ 30^0C in each case. Correctness of connections was then tested by energizing the winding (in star connection) with 110V(a.c.) 3-phase (i.e. about 30% of the design voltage) and having a small iron ball placed inside the stator to serve as rotor. The iron ball was seen to roll round the stator bore *as expected*.

4.1.5 Impregnation and Drying of Winding:

Prior to impregnation, the stator winding was first dried in an oven at a temperature of 110^0C for 2 hours according to [Atabekov, 1980]. Thereafter, the winding was impregnated with SECO Sterling (Air-dry type High Resistant) varnish while still hot for easy penetration. It was then dried again at the same temperature (i.e. 110^0C) for 3 hours (i.e. warm-up stage) and finally at 130^0C (being of Class B insulation) for 6 hours only as in [Atabekov, 1980], being the baking stage of drying.

4.2 Machine Assembly Processes in Brief

Before joining the rotor to the stator the bearings were checked and confirmed OK and cup grease was packed into the bearings. Then, before the final tightening of nuts to secure the end-shields to the machine frame, care was exercised to ascertain that the rotor rotated freely within the stator and that there was no unusual bearing-end sound.

V. Workshop Testing Of Motor

5.1 Pre-Commissioning Tests/Checks:

The results obtained were as presented in Table 5.1.

Table 5.1 Results of Pre-Commissioning Tests/Checks

S/N	ACTION	RESULT	STANDARD	REMARK
1	Winding Insulation Resistance Measurement @ 30^0C for 1 minute, with test voltage of 500V(d.c.).	i)Phase-to-Phase: U1–V1= 75MΩ V1–W1= 93MΩ W1–U1= 77MΩ ii)Phase-to-Frame: U1–Frame = 142 MΩ V1–Frame = 155 MΩ W1–Frame =146 MΩ	1 min. value @ 40^0C not less than (kV+1) MΩ or not less than 1.96(kV+1) MΩ @ 30^0C [Enyong, 2004].	Megohmmeter used: Digital, BM 221, AVO INT. Ltd., England. All Readings OK.
2	Continuity Check	U1 – U2 = 0.00Ω V1 – V2 = 0.00Ω W1 – W2 = 0.00Ω	Continuous Circuit.	Multimeter used: ROBIN, Model OM 500T Taut Band Analog Multimeter. All Readings OK. .
		U1– V1&V2 = ∞ U1– W1&W2 = ∞	Open-circuit.	

5.2 Test-Running (or Commissioning)/Checks:

Shown below in Table 5.2 are the results as realized.

Table 5.2: Test-Running Check Results

S/N	ACTION	RESULTS OBSERVED	REMARKS
1)	***330(a.c.)*** applied through ammeters to machine without load. ***This was the supply voltage level at the time.***	i) Starting Current: 7.0 Amps	Direct-on-Line Starting Current.
		ii) Running Current: 1.2 Amps	No-Load current
		iii) Running Speed: 1500rpm	No-Load Asynchronous Speed.
2)	Watching out for unusual sound or vibration	i) No rubbing sound	a) Rotor Clear from Stator. b) Cooling fan/guard well coupled.
		ii) No croaking sound	Bearing condition OK
		iii) No vibration	Air-gap reluctance relatively even (i.e. machine alignment OK)
		iv) No humming sound.	a) Absence of single-phasing due to internal or external open-circuit. b) Voltage per turn OK
3)	Checking for signs of overheating or burning	i) No over-heating	a) Absence of inter-turn short-circuits. b) Voltage per turn OK c) Conductor S.W.G. OK
		ii) No unusual odour; no smoke	Absence of insulation failure from overheating

Source: From actual Workshop Test-Running Checks on the Motor.

VI. Conclusion:

It can be seen from the test-running exercise that the supply voltage level was 330V (a.c.). Even at this 86.84% of the design voltage, the refurbished motor produced a no-load speed of 1500rpm equal to the synchronous speed. Thus, there is no doubt that with the application of the full design voltage of 380V (a.c.) the full-load speed shall be up to the name-plate stipulated value of 1420rpm, if not more than that.

The following recommendations have become necessary, namely:

(i) A suitable under-voltage relay-protection scheme be should be incorporated in the motor supply system to save the machine from such a breakdown in future.

(ii) Care shall be required to use this motor, henceforth, only up to about 75% of full-load bearing in mind that the same old rotor circuits (magnetic and electrical) are still in place.

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