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Research Paper

Programing the rewinding of a three-phase induction motor stator using interactive computer-aided design technique

Ike S. A [1]*, Enyong P. M [2], Olowu T [3]

[1] University of Benin, Benin-City Nigeria
[2] Auchi Polytechnic Auchi – Nigeria
[3] Department of Electrical &Electronic Engineering,Obafemi Awolowo University, lle-lfe, Osun State
*Corresponding author E-mail: sam.ike@uniben.edu

Abstract

In this paper, a computer program was developed in MATLAB programming language and applied in the refurbishment of defective three-phase squirrel-cage induction motor using the computer-aided design technique/approach. The MATLAB programming language and Computer-Aided Design (CAD) analysis adopted aided the fast computation and convergence of a output result from the developed program that was used in the practical refurbishment of a defective 48-slot 3-phase squirrel-cage induction motor as well as the production of the entire stator winding. The result also revealed the motor as being a 4-pole type which lends itself easily to the lap winding pattern. The winding was practically developed using the program result data, installed, connected and tested. The speed realized from the post-refurbishment workshop test-running using the stroboscopic speed measuring instrument was 1500rpm. This was considered as good performance on no-load condition. The machine was allowed to run for about one hour during the workshop test-running without overheating. The computed output power was 20 kW. The estimated efficiency and power factor by CAD technique were 90 % and 0.9, respectively. These values were considered satisfactory.

Keywords: *Induction Motor; Refurbishment; Cad; Matlab.*

1. Introduction

The squirrel-cage induction motor, particularly the three-phase category, is commonly known as the most-used machine in industrial drive applications [1], [2], [3]. Like every other electrical equipment a three-phase induction motor does break down due to fire incidents, short-circuits, mal-operations, overloading situations and starting duty under single-phasing or under-voltage conditions, thus requiring repair work [4,5]. A 48-slot induction motor that was inadvertently exposed to a discharge from a thunder strike, which resulted to its breakdown, was used in the course of this investigation. A popular road-side technician had difficulties in rewinding the field structure of this machine to be satisfactory running condition. Hence, the developed computer software application package which featured the MATLAB programming language approach was adopted to help in accomplished a proper refurbishment of the motor.
It is informative to note that other programming languages, by means of which the computer functions as desired, include Foxpro, C/C++, Visual Basic, Pascal, Ada, Fortran and Visual C++.[6], [7], [8]. MATLAB is an acronym for Matrix Laboratory developed by Math Works Inc. [9]. This is a software package for high performance and visualization, combining capabilities, flexibilities, reliability and powerful graphics, hence, suitable for engineers and scientists. The most important feature of MATLAB is its programming capability, which is relatively easy to learn and to use, and, which allows user-developed functions [10].

2. The computer software application package

The following programs constitute the computer software application package for reclaiming the defective induction motor. In generating these programs use was made of the host of relevant machine equations, and formulae produced and stored in our data bank. They are not presented here as the focus is not on modeling.

2.1. Input variable collection/storage program (enyoR3phCadInput)

```
%this program collects/stores input variables for induction motor
%redesign/refurbishment purposes.
D=input ('[1] Enter stator bore diameter in cm, D=')
L=input ('[2] Enter stator bore axial length in cm, L=')
b10=input ('[3] Enter stator slot opening in cm, b10=')
b11=input ('[4] Enter slot width at the base of slot mouth, b11=')
b12=input ('[5] Enter slot width at top of bottom semi-circle, b12=')
bt=input (' [6] Enter stator tooth width at the narrow end, bt=')
ds1=input ('[7] Enter total slot depth from opening to bottom, ds1=')
dcs=input ('[8] Enter slot iron core depth in cm, dcs=')
S=input ('[10] Enter stator number of slots, S=')
disp (' ');
disp ('Bav=0.30-0.50 (0.40 suggested for a start).');
disp ('q3orq1=5000-45000 (10000-16000 for smaller motors for a start).');
disp (' (20000-25000 for larger motors for a start).');
disp ('J=3.0-5.0-8.0 (4.0 suggested for a start).');
disp (' ');
Bav=input ('[11] Enter specific magnetic loading in Tesla, Bav=')
q3=input ('[12] Enter specific electric loading in A.C/m, q3=')
J=input ('[13]] Enter current density in A/mm2, J=');
disp (' ');
m=3; f=50; %number of phases & power frequency in Hz, respectively
ang3=60; Ap= 1.2; %angle of spread and Turns fullness factor, respectively
p1=0.184*S*(bt/dcs); %number of pole-pairs (theoretical)
if p1>0 && p1<1.7
p=1;
elseif p1>=1.7 && p1<2.7
p=2;
elseif p1>=2.7 && p1<3.7
p=3;
end
Pn=2*p; %actual number of poles of the motor
run ('functionR3ph');
disp ('"Fine-tuning Adjustment(s) Necessary" is "1"');
disp ('"Further Adjustment(s) Not Required" is "0" ');
disp (' ');
Selct=input ('Enter your choice by a number please, Selct=')
if Selct==1
disp ('Fine-tuning Adjustment(s) Exercise');
disp (' ');
run ('functionR3ph');
elseif Selct==0
disp ('Further Adjustment(s) Unnecessary');
disp (' ');
disp ('DONE');
end
```

2.2. Three-phase motor redesign computational and display program (enyoR3phMotComp)

```
%This program computes and/or selects the Number of Turns, Number
%of Coils & the Span, Conductor Size, Air-gap, Number of Poles,
%Full-load Power Ouput, and other operational quantities and displays
```

```
%the needed technical data for the redesign/refurbishment of an
%Existing Three-phase Induction Motor.
disp (' THREE-PHASE INDUCTION MOTOR STATOR WINDING RE-DESIGN');
disp (' ');
if Pn==6 && S==48 && ang3~=180
disp ('Wrong Application!');
disp ('ang3 should be 180 in this case');
ang3=input ('Enter the correct Angle of Spread, ang3= ')
elseif Pn==6 && S==54 && ang3~=60
disp ('Wrong Application!');
disp ('ang3 should be 60 in this case');
ang3=input ('Enter the correct Angle of Spread, ang3= ')
end
Pb= (360*p)/ang3; %number of phase belts
Q3_1=S/Pb; %number of coils per phase-belt in lap (basket) winding;
Q3_2=4; %number of coils per phase-belt in concentric winding of
%S=48 and ang3=180
if S==48 && Pn==6 && ang3==180
Q3=Q3_2;
else
Q3=Q3_1;
end
a_1=(2*pi*p)/S; %slot pitch in radians elect
a_2=a_1/2; %slot pitch in radians elect for S=48
if S==48 && Pn==6 && ang3==180
a=a_2;
else
a=a_1;
end
g= (pi/a)-1; %longest coil span in multiples of slot pitch angle, a.
y=9:2: g; %coil spans for windings of 16 slots per phase-belt
Kp= sin (g*a/2); %pitch factor
ang_3= (ang3/180)*pi; %angle of spread in radians elect
Kd= sin (0.5*ang_3)/(Q3*sin(0.5*ang_3/Q3)); %distribution factor
den= 0;
for y=9:2:g
den= den+sin (y*a/2);
end
num= 0;
for y=9:2:g
num= num+(sin(y*a/2))^2;
end
Kw11=Kp*Kd; %winding factor for lap phase-belts where S~=48
Kw12=num/den; %winding factor for concentric phase-belts spanning 16 slots
if S==48 && Pn==6 && ang3==180
Kw1=Kw12;
else
Kw1= Kw11;
end
vol= D^2*L; %machine bore volume in cm^3
run('functionPofComp'); %output power computing function (see appendix 1)
if Pof3<10
s=0.05;
elseif Pof3>=10 && Pof3<30
s=0.045;
elseif Pof3>=30 && Pof3<56
s=0.04;
elseif Pof3>=56 && Pof3<80
s=0.035;
end
rpm= round(60*f*(1-s)/p); %motor rotor speed
run ('functionR3pheffpf'); %efficiency and p.f. selector (see appendix 2)
```

```
Iph= (Pof3*10^3)/(m*eff*pf*Vph);
Number_of_Poles=Pn
Number_of_Stator_Slots=S
v= (pi*D*f/p)*10^-2; %computes peripheral speed in m/s
Peripheral_Speed_value_in_mps=v
a1=pi*D/S; %gives slot pitch in cm
Slot_Pitch_value_in_cm=a1
lg=(0.013+0.003*D/sqrt(p))*10; %air-gap radial length (mm)
Air_Gap_in_mm=lg
Number_of_Phase_Belts=Pb
Number_of_Coils_per_Belt=Q3
d10=0.1; %depth of slot lip in cm for general use
d11=1.5*d10; %depth of slot mouth or slanting wedge area in cm
d12=ds1-(0.5*(b12+ (5*d10)));
Asg=0.5*((d11*(b10+b11)) + (d12*(b11+b12)) + (pi*b12^2/4))*10^2; %gross slot
%area (mm^2)
Fp= (pi*Bav*D*L)/ (Pn*10^4); %flux per pole
Nph=round ((Ap*Vph)/ (f*Fp*Kw1)); %practical number of series turns per phase
Npb=round (Nph/Pb); %practical number of series turns per phase-belt
if ang3~=180
Winding_Turns_per_Phase=round (Nph)
end
Zph=2*Nph; %total number of conductors per phase
Z=m*Zph; %total number of conductors on the motor
Zs=Z/S; %total number of conductors per slot
nc= 3; %number of coils per phase-belt of concentric winding
if ang3~=180
Number_of_Conductors_per_Slot=round(Zs)
end
Zc1=Zs/2; %number of conductors per coilside of lap (basket) winding
Zc2=Zs; %number of conductors per coilside of concentric winding of 1 layer
if ang3==180
Zc=Zc2;
else
Zc=Zc1;
end
if ang3~=180
Number_of_Conductors_per_CoilSide_or_Layer=round(Zc)
end
if ang3~=180
Coil_Span_in_Slotpitches=g
end
Ac1=Iph/J; %cross-sectional area of single bare copper conductor (mm^2)
Bare_Copper_Conductor_Xsectional_Area_in_sqmm=Ac1
dc1=sqrt(4*Ac1/pi); %diameter of the required bare copper conductor
run ('functionMotSWG'); %table of standard wire gauge (see appendix 3)
S_W_G1=interp1 (Area, SWG, Ac1,'nearest'); %standard wire gauge of the required
%bare round copper conductor
Round_Copper_Conductor_Standard_Wire_Gauge=S_W_G1
disp ('for 1-Wire-in-Hand application');
disp (' ');
run ('function3phSwgAlt'); %multiple-wire-in-hand S.W.G selector (appendix 4)
disp(' ');
s_w_g= [10 12 13 15 19 21 23 26 31 34 40];
ena1= [0.11 0.10 0.08 0.07 0.06 0.055 0.04 0.035 0.025 0.02 0.017];
enam= interp1(s_w_g,ena1,S_W_G1,'nearest'); %light enamel covering for
%round conductors
Ac2= (pi*(dc1+enam)^2)/4; %cross-sectional area of enamel-covered single %copper conductor
SF= (Ac2*Zs)/Asg; %slot space factor with round copper conductor
disp ('FIND BELOW OTHER MACHINE DETAILS');
disp (' ');
```

```
if S==48 && Pn==6 && ang3==180
Individual_Spans_of_Phase_Belt_Coils=9:2: g
disp ('Turns of Phase-Belt Coils beginning with the Outer Coil');
disp (' ');
Pb_coil1=round (Npb*(sin (g*a/2))/den) %the outermost coil turns of a
%phase belt
Pb_coil2=round (Npb*(sin ((g-2)*a/2))/den) %the next inner coil turns
%of a phase-belt
Pb_coil3=round (Npb*(sin ((g-4)*a/2))/den) %the far inner coil turns
%of a phase-belt
Pb_coil4=round (Npb*(sin ((g-6)*a/2))/den) %the innermost coil turns
%of a phase-belt
Machine_Winding_pattern= ('Concentric Winding of Single Layering')
end
Expected_Full_Load_Output_Power_in_kW=Pof3 %mechanical full-load output
%power in kW as expected
Expected_Full_Load_Input_Current_in_Amps=Iph %full-load input current in
%Amps as expected
Rotor_Speed_in_rpm=rpm
Peripheral_Speed_in_mps=v
Slot_Pitch_in_cm=a1
Air_Gap_Radial_Length_in_mm=lg
Stator_Bore_Axial_Length_in_cm=L
Stator_Bore_Diameter_in_cm=D
Gross_Xsectional_Area_of_Slot_in_sqmm=Asg
Specific_Magnetic_Loading_in_Tesla=Bav
Specific_Electric_Loading_in_ACpm=q3
Slot_Space_Factor_with_Round_Copper_Conductors=SF
Current_Density=J
disp(' ');
if SF>=0.25 && SF<=0.40 && q3>=10000 && q3<40000
disp ('Redesign Computations are Completed');
disp ('Values of SF and q3 are Satisfactory.');
disp ('SCROLL UP and VIEW THE OTHER DETAILS, please.');
disp (' ')
elseif SF>=0.40 && SF<=0.25 && q3>40000 && q3<=10000
disp ('SF and/or q3 not satisfactory.');
disp ('Standard Values are SF=0.25-0.40p.u.; q3=5000-45000A.C/m');
disp (' ');
disp ('Pof3, Bav and/or J can be adjusted for acceptable result(s).');
disp (' ');
disp ('Increase Pof3 to Increase SF,q3. [Opposite Action to Decrease]');
disp ('Increase Bav to Decrease SF,q3. [Opposite Action to Increase]');
disp ('Increase J to Decrease SF only. [Opposite Action to Increase]');
disp (' ');
run ('functionR3ph');
end
```

3. Re-design/refurbishment of the three-phase motor

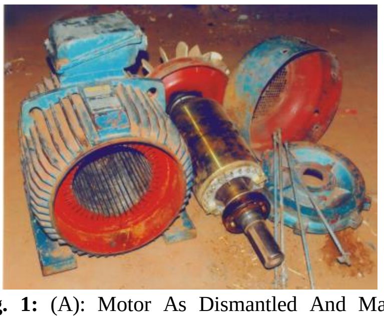

Fig. 1: (A): Motor As Dismantled And Made Ready For Physical Measurement & Inspection.

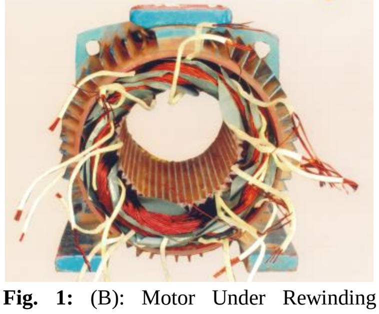

Fig. 1: (B): Motor Under Rewinding Process.

Fig. 1: (C): Motor As Re-Assembled And Made Ready For Workshop Test-Running.

3.1. Input data from machine measurements & inspection

Table 1: Input Data from Machine Measurements/Inspection

S/N	QUANTITY	VALUE	S/N	QUANTITY	VALUE
1	Stator Bore Diameter, D	19.70cm	6	Overall Depth of Slot, d_{s1}	02.55cm
2	Stator Bore Axial Length, L	25.90cm	7	Tooth Width at Narrow End, b_t	00.80cm
3	Stator Slot Opening, b_{10}	00.35cm	8	Stator Core Depth, d_{cs}	03.00cm
4	Slot Width at Mouth Base, b_{11}	00.52cm	9	Number of Stator Slots, S	48
5	Slot Width at Top of Bottom Semi-circle, b_{12}	01.8cm	10	Number of Motor Phases, m	3

3.2. Running the computer software application package

After inputting the data above the result of running the software application package or CADTECH, as obtained from the MATLAB Workspace, is as follows:

a) Summary of Winding Design Parameters from Cadtech Output

1) No. of Winding Phase-Belts = 12
2) No. of Coils per Phase-Belt = 4
3) Phase-belt Spreading in degree (elect) =60.
4) Winding Coil Span = 1—12 slots (in all)
5) Winding Coil Turns = 33 (in all)
6) Conductor Size = SWG 18 of 4 Wires-in-Hand
7) Pattern of Stator Winding = Lap (Basket)
8) Output Power, Pof1 = 20kW
9) Voltage/Frequency = 380V, 50Hz, resp.
10) Input Phase/Line Currents = 21.66A, 37.51A, resp.
11) Specific Magnetic Loading = 0.4 Tesla
12) Specific Electric Loading = 28,339 A-Cond/m
13) Current Density = 5.0 A/mm2
14) Full-Load Rotor Speed = 1433rpm
15) Efficiency/Power Factor (estimated) = 0.90 p.u., 0.90, resp.
16) Space Factor = 0.2639
17) Motor Estimated Normal Slip = 0.045

b) Sectional Winding Diagram from Cadtech Output

Figure 2 shows the complete sectional winding diagram of the motor from CADTECH output.

```
|<------------------- NORTH ------------------->|<--Poles
|        A        |        -C        |        B         |<--Phase Belts
|a1 |a1 |a1 |a1 |.c1|.c1|.c1|.c1|b1 |b1 |b1 |b1 |<--Top Layer
|a4 |a4 |a4 |.c4|.c4|.c4|.c4|b4 |b4 |b4 |b4 |.a1|<--Buttom Layer
  1    2    3   4    5   6    7   8    9   10   11   12 <--Slot Numbers

|<------------------- SOUTH ------------------->|<--Poles
|       -A        |        C         |        -B        |<--Phase Belts
|.a2|.a2|.a2|.a2|c2 |c2 |c2 |c2 |.b2|.b2|.b2|.b2|<--Top Layer
|.a1|.a1|.a1|c1 |c1 |c1 |c1 |.b1|.b1|.b1|.b1|a2 |<--Buttom Layer
 13  14 15 16  17  18 19  20  21  22  23  24 <--Slot Numbers

|<------------------- NORTH ------------------->|<--Poles
|        A        |        -C        |        B         |<--Phase Belts
|a3 |a3 |a3 |a3 |.c3|.c3|.c3|.c3|b3 |b3 |b3 |b3 |<--Top Layer
|a2 |a2 |a2 |.c2|.c2|.c2|.c2|b2 |b2 |b2 |b2 |.a3|<--Buttom Layer
 25  26  27 28  29 30  31 32  33  34  35 36 <--Slot Numbers

|<------------------- SOUTH ------------------->|<--Poles
|        -A       |         C        |        -B        |<--Phase Belts
|.a4|.a4|.a4|.a4|c4 |c4 |c4 |c4 |.b4|.b4|.b4|.b4|<--Top Layer
|.a3|.a3|.a3|c3 |c3 |c3 |c3 |.b3|.b3|.b3|.b3|a4 |<--Buttom Layer
 37  38 39  40  41 42  43  44  45 46  47 48 <--Slot Numbers
```

Figure 2 is the lap (Basket) Winding of the 48-slot, 4-pole, 3-phase Motor. NB: The dot (.) indicates the "finish" sides of the belt coils.

3.3. Rewinding the stator or field structure

Following the winding schematic diagram as detailed in the software output above, the machine field structure was rewound and duly connected as shown in Fig.3, following examples in [11], [12] as well as other standard works.

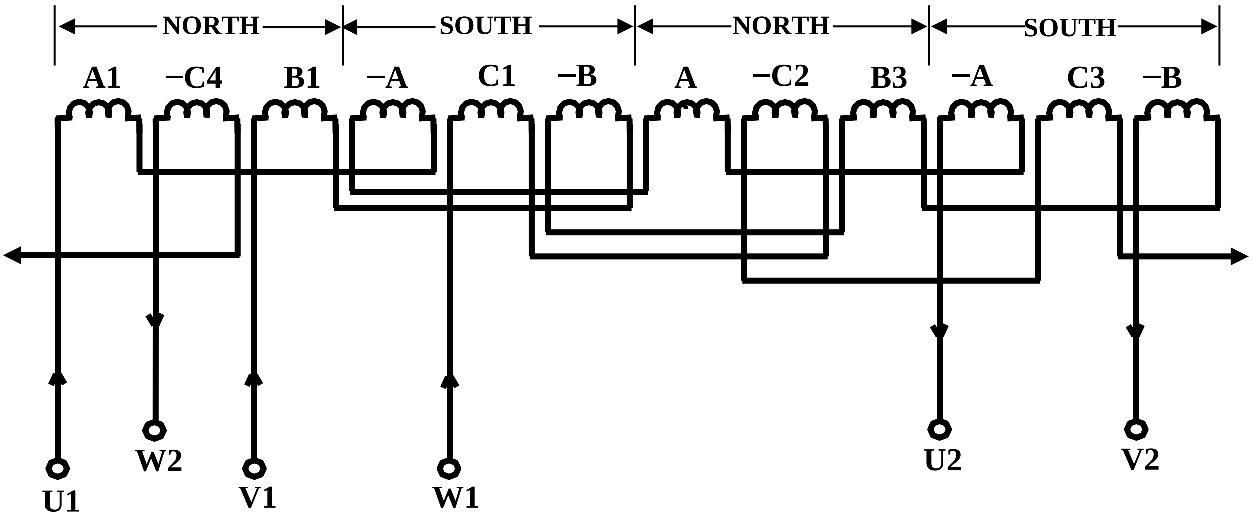

Fig.3: Diagram Showing the Series/Series Connection of the 12 Phase-Group Coils of the Stator Winding Under 4 Poles, Resulting in the Final 6 Terminal Leads to Be Connected Either in Star (for Low Speed Operation) Or Delta (for Rated Speed Application).

4. Testing, conclusion & recommendation

4.1. Workshop test-running of the motor

The results obtained are presented in Table 2A.

Table 2A: Results of Pre-Commissioning Tests/Checks

S/N	ACTION	RESULT	STANDARD	REMARK
1	Winding Insulation Resistance Measurement @ 30^{0}C for 1 minute, with test voltage of 500V (d.c.).	i)Main-to-Aux: U1–X1 = 54MΩ ii)Main-to-Frame: U1–Frame = 87MΩ iii) Aux-to-Frame: X1–Frame = 90MΩ	1 min. value @ 40^{0}C not less than (kV+1) MΩ or not less than 1.96(kV+1) MΩ @ 30^{0}C [6].	Megohmmeter used: Digital, BM 221, AVO INT. Ltd., England. All Readings OK.
2	Continuity Check	U1 – U2 = 0.00Ω X1 – X2 = 0.00Ω U1– X1&X2 = ∞ X1– U1&U2 = ∞	Continuous Circuit. Open-circuit.	Multimeter used: ROBIN, Model OM 500T Taut Band Analog Multimeter. All Readings OK.

Test-running (or commissioning)/checks:
Shown below in Table 2B are the results as realized.

Table 2b: Test-Running Results

ACTION	RESULT OBSERVED	REMARKS
220V (a.c.) applied.	i) Running Current: 3.7 Amps	No-load Running Current (Clip-on ammeter used in taking measurement).
	ii) Running Speed: 1500rpm	No-load Rotor Speed assuming the synchronous speed value as okayed by [13], [14].

4.2. Conclusion

The 20-kW, 48-slot, 4-pole, 50Hz, 3-phase squirrel-cage induction motor was seen to have been satisfactorily refurbished. The design was made a lot easier and appropriate by means of computer-aided technique referred to here as CADTECH. Hence, CADTECH is recommendable to induction motor repair outfits for the reclamation of abandoned or defective induction motors that populate our industry's local industries, since by CADTECH, any defective induction motor can be easily and satisfactorily refurbished from first principles, so to say, i.e. without recourse to name-plate details or previous winding data.

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