Performance Appraisal of a Direct-Current Motor Through an Experimental Determination of Its Rotational Inductances and Open-Circuit Curves

Peter Michael Enyong, Evaristus Bola Obaitan

Abstract— A laboratory dc motor was investigated in terms of its steady-state performance characteristics and parameters. The rotational inductances G_1 and G_2 of the machine were first determined under shunt- and series-connected operational conditions (respectively) as was required. Relevant dc motor equations were generated and the values of G_1 and G_2 duly applied thereto for the realization of the needed performance characteristics and parameters. In this paper, the authors present a brief review of the dc motor highlighting areas of advantage over its ac counterpart, amongst other things. Details of the no-load test and winding dc resistance test necessary in the experimental determination of G_1 and G_2 are given. Eight relevant graphs each were MATLAB-plotted for both shunt and series operational conditions. Open-circuit characteristics (OCC's) of the machine were similarly plotted for both shunt and series modes of operation. The rotational inductances of the motor were determined as 1.6H and 2.8H, respectively. The maximum starting current, net output torque, shaft or output power, overall efficiency and speed regulation of the motor as key performance parameters were 111A, 19N-m, 2156W, 78% and 11%, respectively, under shunt operation. Similar manual computations for the series case showed the motor gainfully applicable to load currents of 1Amp and below; whereas, the armature circuit was rated 11.4A, 220V. The reason for this had to do with the very high field winding resistance which was much more favourable to the shunt than the series operation. From the OCC's the machine was also seen to be markedly prone to saturation under series operation as it exhibited an estimated saturation factor of 3.19 p.u.; whilst, under shunt operational condition a very acceptable value of 1.11 p.u. was realized. However, the use of field diverters is suggested for the machine performance to be considerably improved under series-connected version of operation.

Index Terms—Inductances, Rotational, Shunt-Series Motor, Performance.

◆

1 INTRODUCTION

THE dc motors in the electrical power laboratory of the Federal Polytechnic, Auchi, Nigeria were found to be lacking in the necessary documentation as touching performance information, besides manufacturer's name-plate details. In view of this deficiency, experimental results could not be immediately checked for accuracy, for proper instruction of students. There was thus the need to have the relevant performance data of a sample laboratory dc motor generated, documented and kept as a reference data bank to that effect. However, the choice of approach (mostly for ease of accomplishment) was by means of the motor rotational inductances, which were to be obtained experimentally and applied to the significant dc motor equations for the realization of the said objective.

A dc motor is one of the electromechanical energy converting devices in which the energy converts from electric to mechanical form [1],[2]. Working basically by means of the electromagnetic induction principle as enunciated by Michael Faraday[3], it possesses armature and field structure/windings to which direct current (dc) is applied, i.e. current having continuously constant magnitude and the same direction of flow. Fig. 1 shows the principal parts of a dc motor as found in [2] and Fig.2 shows the laboratory dc motor in question.

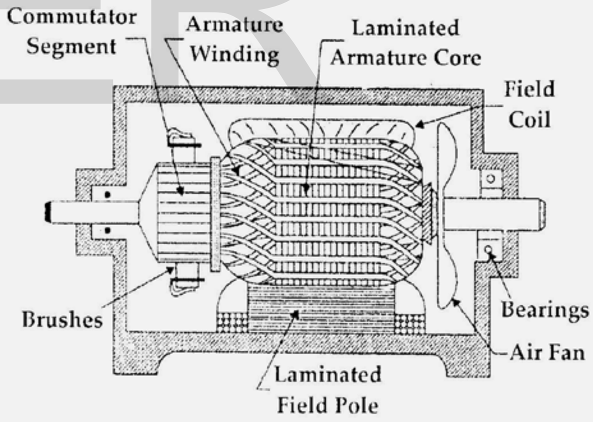


Fig. 1: Longitudinal Section showing the Main Components of a Direct Current Motor

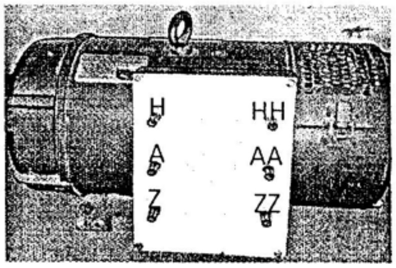


Fig. 2: The Laboratory DC Machine showing Pairs of Winding Terminals: H-HH for the Compole Winding; A-AA for the Armature Winding; and Z-ZZ for the Field Winding.

Apart from adaptability to power sources and safety considerations, the dc motor is often preferred in speed control measures to the ac motor due to its simplicity and relative cheapness as a control device, especially where wide speed range control is required. Also, its high torque production ability at low speed makes dc motors a good alternative apparatus to gear motors in many applications [4]. Hence, dc motors continue to command industrial import to date.

Inductance, L, is the property of every electrical device made up of a core-and-coil arrangement, which is responsible for its ability to present a lagging (or conventionally +ve) reactive factor (i.e. +sinφ) when an alternating current (ac) flows through its coil or winding [5]. It is important to state here that owing to the commutator (a special mechanical switch) acting as a frequency changer [6], the dc applied to the armature winding is converted into an alternating current (indeed, a current that reverses direction following the speed of armature rotation).

The nature of inductance exhibited by an electromechanical energy converter, as an inductive apparatus, will usually depend on its operational condition. When under open-circuit or no-load operation, the machine will exhibit an inductance arising from the exciting current drawn by it. Since this current is informed by the electromechanical energy conversion process, which culminates in the machine shaft rotation, the consequent inductance developed is referred to as rotational or motional inductance as in [7], where it is designated, G. By means of accurate value of G, duly determined by an open-circuit test and whose value will depend as well on the manner of armature/field winding connection (i.e. whether shunt or series connection), the performance parameters of a dc motor can be obtained, via the relevant and related dc machine equations.

The dc motor under investigation was a 2.5kW, 220V, 1450-1550rpm, SCOTT motor with armature circuit current of 11.4A and field circuit current of 0.7-1.09A. It was designed and constructed for use as either a series- or shunt-connected motor.

2 MATERIALS AND METHODS

2.1 Materials

Under this sub-section a presentation of the relevant performance equations shall be made serving as the necessary working materials, amongst other things, towards the realization of the objects of this study. Of course, the generation of performance equations of an electrical machine is often accomplished by means of its equivalent circuit parameters. To this end, Fig. 3 (a) and (b) have been provided showing the equivalent circuit of the dc motor under shunt- and series-connected operational modes, respectively; where the compole or commutating pole winding (whose dc resistance is r_c) is often connected in series with the armature to help to ameliorate the effect of armature reaction [8], [9].

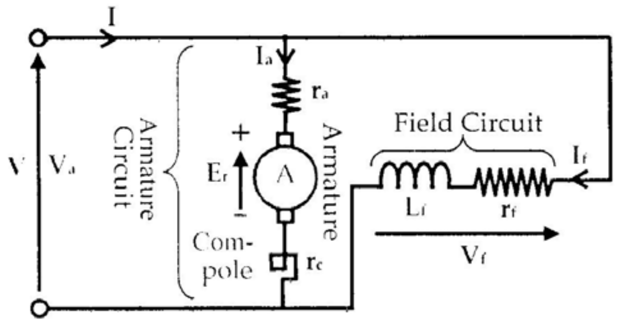


Fig. 3(a): Shunt-Connected DC Motor Equivalent Circuit

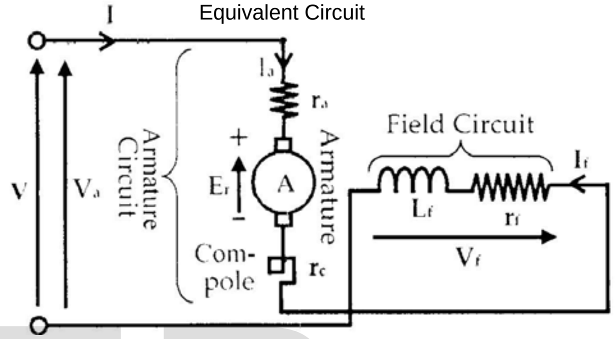


Fig. 3(b): Series-Connected DC Motor Equivalent Circuit

The motor performance equations are then generated as detailed in the sub-sub-sections that follow.

Equations for the Rotational Inductances:

In the shunt- and series-connected versions of the dc motor, the terminal voltage, V, and the input current, I, will have the following expressions

$V = V_a = V_f$ and $I = I_a + I_f$ (for the shunt-connected version); and

$V = V_a + V_f$ and $I = I_a = I_f$ (for the series-connected version) (1)

The q-axis *armature rotational e.m.f* (E_r) of a d.c. motor under steady-state operation is generally given (in Volts) as

$$E_r = [(N_a/\pi)(p/a)]\omega_r\Phi = K\omega_r\Phi \ \{\text{i.e. } K = (N_a/\pi)(p/a)\} \quad (2)$$

where Φ – Flux per pole; N_a – Number of turns of armature winding, p – Number of pole-pairs and 'a' – Number of parallel paths. The flux is usually a nonlinear function of the current according to [7]. Thus, the terminal voltage of a d.c. motor can be given as

$V = E_r + I_aR_a$ (for the shunt); and

$V = E_r + I(R_a+R_f)$ (for the series) (3)

It has to be noted that by neglecting magnetic saturation and armature reaction (which amounts to a linearization approach), the term KΦ can be replaced by GI_f, according to [7], [8]. Hence, to satisfy the purpose of this work, "(2)" shall now be restated as

$$E_r = GI_f\omega_r \quad \text{(Volts)} \quad (4)$$

Substituting for E_r in "(3)" and differentiating G (into G_1 and G_2) we can write

$$V = G_1 I_f \omega_r + I_a R_a \text{ (for shunt); and}$$
$$V = I[G_2\omega_r + (R_a+R_f)] \text{ (for series)} \qquad (5)$$

So that

$$G_1 = (V - I_a R_a)/(I_f \omega_r) \text{ (for shunt); and}$$
$$G_2 = \{V - I(R_a+R_f)\}/(I\omega_r) \text{ (for series)} \qquad (6)$$

R_a and R_f being the total armature and field circuit resistances, respectively; {i.e. $R_a = (r_a + r_c)$ and $R_f = r_f$}.

Equations reflecting Speed /Current Relationship:

From "(6)" we have

$$\omega_r = (V - I_a R_a)/(G_1 I_f) \text{ (for shunt); and}$$
$$\omega_r = \{V - I(R_a+R_f)\}/(G_2 I) \text{ (for series)} \qquad (7)$$

Equations reflecting Torque /Current Relationship:

The electromagnetic or developed torque, T_{dev}, of a d.c. motor under steady-state operation is given (in N-m) as $T_{dev} = K\Phi I_a$ (generally). Substituting for $K\Phi$ as earlier given, we have

$$T_{dev} = G_1 I_f I_a \text{ (for shunt); and}$$
$$T_{dev} = G_2 I_f I_a = G_2 I^2 \text{ (for series)} \qquad (8)$$

Equations reflecting Torque/Speed Relationship:

From "(5)" we can write, respectively

$$I_a = (V - G_1 I_f \omega_r)/R_a;\ I = V/\{G_2\omega_r + (R_a+R_f)\}$$

Substituting for I_a and I accordingly in "(8)" gives

$$T_{dev} = G_1 I_f (V - G_1 I_f \omega_r)/R_a \text{ (for shunt) and}$$
$$T_{dev} = G_2[V/\{G_2\omega_r + (R_a+R_f)\}]^2 \text{ (for series)} \qquad (9)$$

Equations reflecting Power /Speed Relationship:

The converted or developed power, P_{dev}, of a d.c. motor under steady-state operation is generally given in terms of electromagnetic or developed torque, T_{dev}, as

$$P_{dev} = \omega_r T_{dev} = \omega_r[G_1 I_f (V - G_1 I_f \omega_r)/R_a] \text{ (for shunt);}$$

and

$$P_{dev} = \omega_r[(G_2(V/\{G_2\omega_r + (R_a+R_f)\})^2] \text{ (for series)}$$

(10)

Equations reflecting Emf/Speed Relationship:

Also, the developed power is given by

$$P_{dev} = E_r I_a;\text{ meaning } E_r I_a = \omega_r T_{dev};\text{ so that}$$
$$E_r = \omega_r T_{dev}/I_a \text{ (for shunt) and}$$
$$E_r I = \omega_r T_{dev};\text{ and } E_r = \omega_r T_{dev}/I \text{ (for series)} \qquad (11)$$

Other relevant DC Motor equations as in [8] include,

Total Copper Loss (P_{cu}) Equation:

$$P_{cu} = P_{a(cu)} + P_{f(cu)}$$

{i.e. Armature copper loss + Field copper loss}

$$P_{cu} = I_a^2 R_a + I_f^2 R_f \text{ (for shunt); and}$$
$$P_{cu} = I^2(R_a+R_f) \text{ (for the series)}$$

(12)

Total Motor Losses (P_{loss}) Equation:

$$P_{loss} = P_{cu} + P_{mech} + P_{add} \qquad (13)$$

P_{mech} is the *Total Mechanical Losses* (or summarily *Rotational Losses)* comprising *Eddy-current, Hysteresis, Bearing Friction & Windage Losses* and has been seen to be approximately proportional to motor speed according to [10]. They also include *brush-contact frictional loss* as in [7] and are essentially equal to the power developed by the machine during no-load operation. P_{add} is the stray or additional losses of sundry nature rather difficult to evaluate. However, according to [9] stray losses are often estimated at 1% output for dc motors of 150kW & above ratings and are usually neglected for dc motors of lower ratings. Thus, as affecting this test motor we shall have $P_{add} = 0W$.

Input Power (P_{in}) Equations:

$$P_{in} = VI_{in} = P_{out} + P_{loss} = P_{dev} + P_{cu} \qquad (14)$$

where $I_{in} = I$, as in Fig. 3(a) and Fig. 3(b)

Power Developed (P_{dev}) & Output (P_{out}) Equations:

$$P_{dev} = P_{in} - P_{cu};\ P_{out} = P_{dev} - (P_{mech} + P_{add}) \qquad (15)$$

Efficiency (η) Equation:

$$\eta = P_{out}/P_{in} = P_{out}/(P_{out} + P_{loss})$$
$$= (P_{in} - P_{loss})/P_{in} = \{1 - (P_{loss}/P_{in})\} \text{ p.u.} \qquad (16)$$

Speed Regulation (ω_{reg}) Equation:

$$\omega_{reg} = \{[\omega_{ro} - \omega_r]/\omega_r\}*100\%$$

(17)

where ω_{ro} and ω_r are no-load and full-load angular velocity values, respectively.

2.2 Methods:

No-load test is required in the determination of G_1 and G_2 as in [8] (where it is designated as K). And considering "(6)", the values of the total armature and field circuit resistances, R_a and R_f, are also required for this purpose. Hence, laboratory tests were carried out to that effect in this work. Figure 4 shows pictorially the apparatus set up for the relevant experimental exercise.

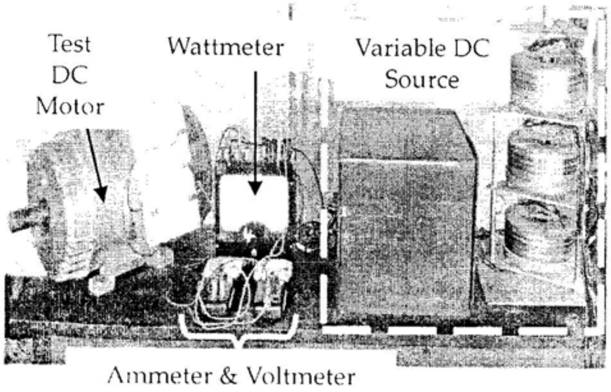
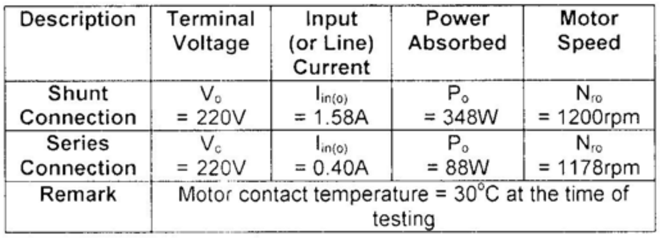


Fig. 4: Apparatus as setup for Open-Circuit and Resistance Tests

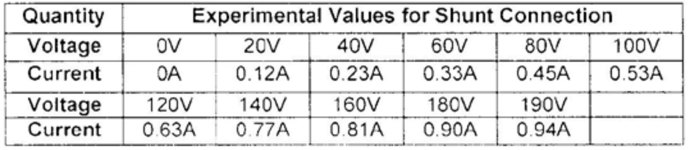
Tables 1, 2(a) and 2(b) show the results of the no-load test carried out. The resistance test was conducted using the ammeter-voltmeter method as in [11] and the test data are given in Table 3.

TABLE 1: Current, Power and Motor Speed on No-load



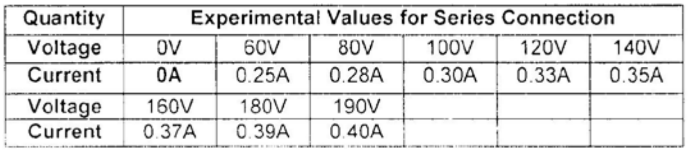
Description	Terminal Voltage	Input (or Line) Current	Power Absorbed	Motor Speed
Shunt Connection	V_o = 220V	$I_{in(o)}$ = 1.58A	P_o = 348W	N_{ro} = 1200rpm
Series Connection	V_c = 220V	$I_{in(o)}$ = 0.40A	P_o = 88W	N_{ro} = 1178rpm
Remark	Motor contact temperature = 30°C at the time of testing			

TABLE 2(a): Data for Open-Circuit Characteristics (OCC) Plotting (for shunt connection)



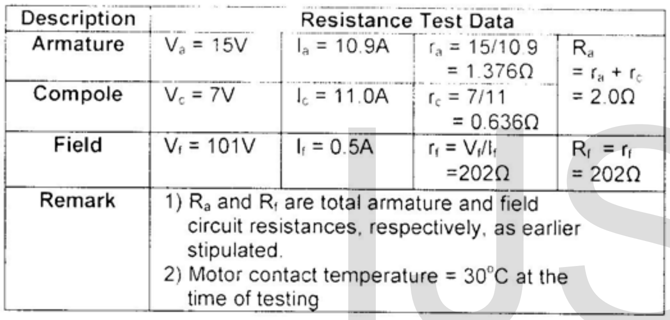
Quantity	Experimental Values for Shunt Connection					
Voltage	0V	20V	40V	60V	80V	100V
Current	0A	0.12A	0.23A	0.33A	0.45A	0.53A
Voltage	120V	140V	160V	180V	190V	
Current	0.63A	0.77A	0.81A	0.90A	0.94A	

TABLE 2(b): Data for Open-Circuit Characteristics (OCC) Plotting (for series connection)



Quantity	Experimental Values for Series Connection					
Voltage	0V	60V	80V	100V	120V	140V
Current	0A	0.25A	0.28A	0.30A	0.33A	0.35A
Voltage	160V	180V	190V			
Current	0.37A	0.39A	0.40A			

TABLE 3: Results of the DC Resistance Tests on the Motor



Description	Resistance Test Data			
Armature	V_a = 15V	I_a = 10.9A	r_a = 15/10.9 = 1.376Ω	$R_a = r_a + r_c$ = 2.0Ω
Compole	V_c = 7V	I_c = 11.0A	r_c = 7/11 = 0.636Ω	
Field	V_f = 101V	I_f = 0.5A	$r_f = V_f/I_f$ =202Ω	$R_f = r_f$ = 202Ω
Remark	1) R_a and R_f are total armature and field circuit resistances, respectively, as earlier stipulated. 2) Motor contact temperature = 30°C at the time of testing			

3 RESULTS AND DISCUSSION

3.1 Results:

The Rotational Inductance Values:

For the shunt-connected version –

I_f = 220/202 = 1.089A (constant); $I_{ao} = I_{in(o)} - I_f$ = 1.58 – 1.089 = 0.491A

$E_{ro} = V - I_{ao}R_a$ = 220 – (0.491*2) = 219V.

$\omega_{ro} = 2\pi(N_{ro}/60) = 2\pi*(1200/60)$ = 125.7 rad.(elect.)/sec.

$P_{in(o)} = P_o$ = 348W (from test)

$\therefore$ $G_1 = E_{ro}/(I_f*\omega_{ro})$ = 219/(1.089*125.7) = 1.6Henry.

For the series-connected version –

$I_{in(o)} = I_{ao} = I_{fo} = I_o$ = 0.40A

$E_{ro} = V - I_o(R_a + R_f)$ = 220 – (0.40*204) = 138.4V.

$\omega_{ro} = 2\pi(N_{ro}/60) = 2\pi*(1178/60)$ = 123.4 rad.(elect.)/sec.

$P_{in(o)} = P_o$ = 88W (from test)

$\therefore$ $G_2 = E_{ro}/(I_o*\omega_{ro})$ = 138.4/(0.4*123.4) = 2.8Henry.

The Motor Performance Graphs:

For the shunt-connected version –

The eight selected MATLAB-generated graphs for the shunt-connected version are as given in Fig. 5 – 12 that follow.

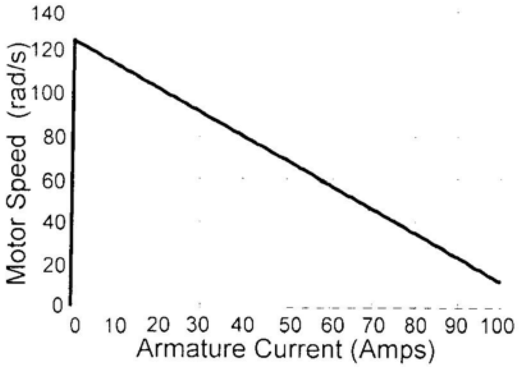


Fig. 5: Graph of Speed versus Load Current

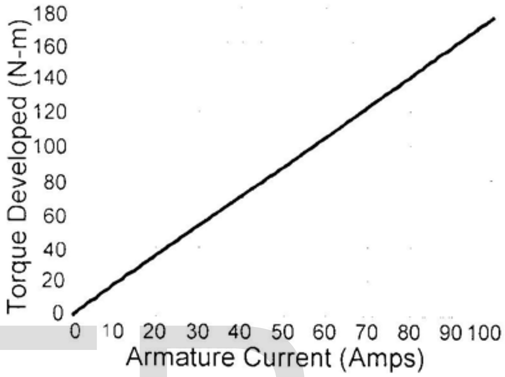


Fig. 6: Graph of Torque versus Load Current

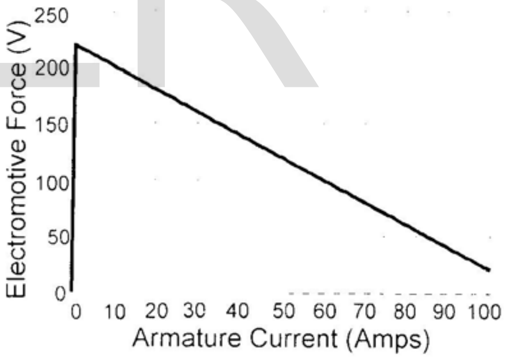


Fig 7: Graph of EMF versus Load Current

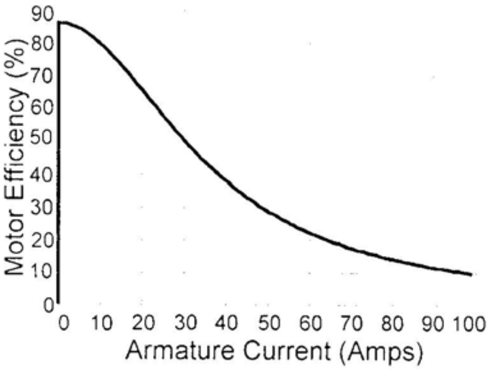


Fig. 8: Graph of Efficiency versus Load Current

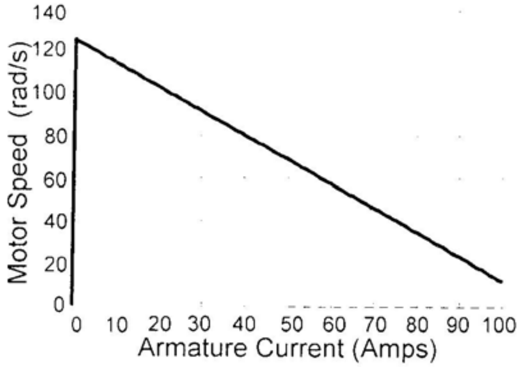


Fig. 9: Graph of Torque versus Speed

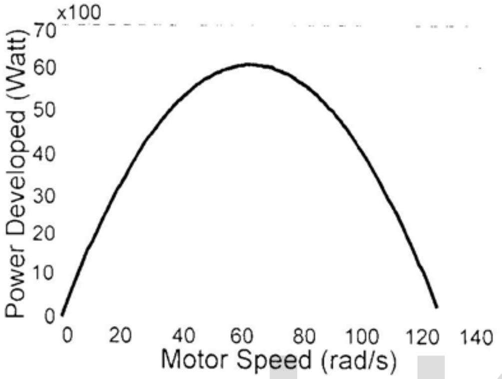


Fig.10: Graph of Power versus Speed

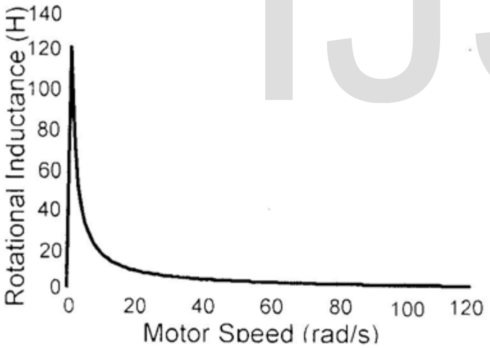


Fig.11: Graphs of Rotational Inductance versus Speed

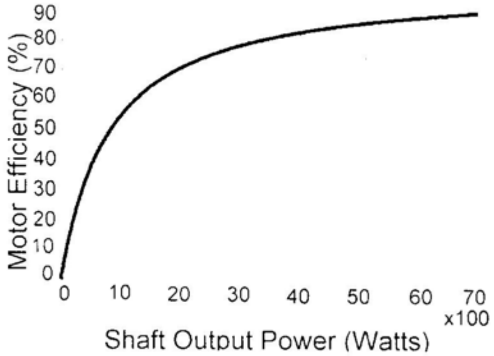


Fig. 12: Graph of Efficiency versus Power Developed

For the series-connected version –

See the eight selected MATLAB-generated graphs for the series-connected version as given in Fig. 13 – 20 that follow.

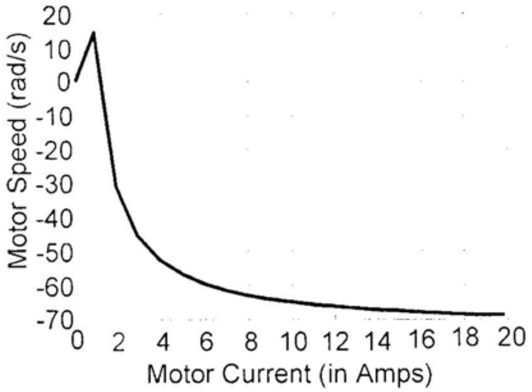


Fig. 13: Graph of Speed versus Current

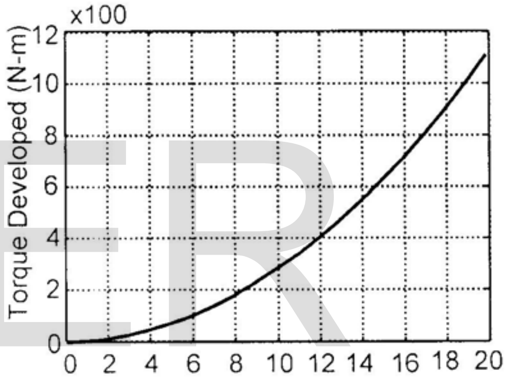


Fig. 14: Graph of Torque versus Current

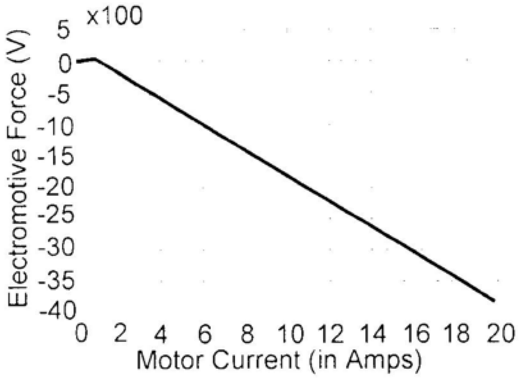


Fig 15: Graph of EMF versus Current

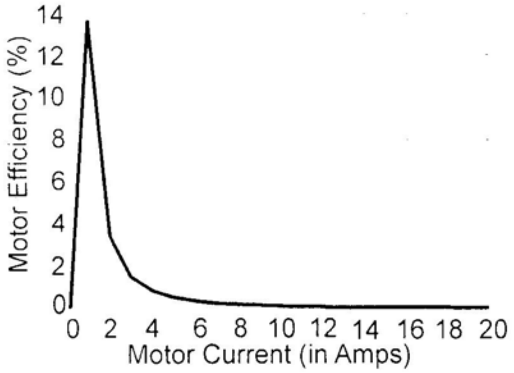


Fig. 16: Graph of Efficiency versus Current

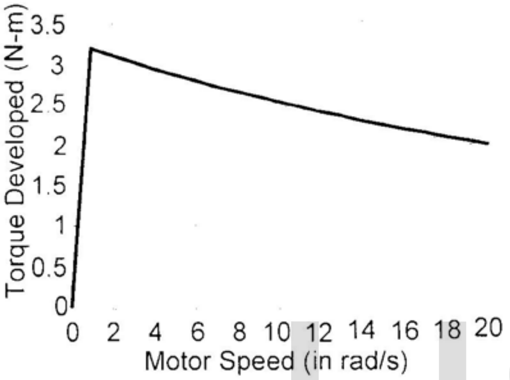


Fig. 17: Graph of Torque versus Speed

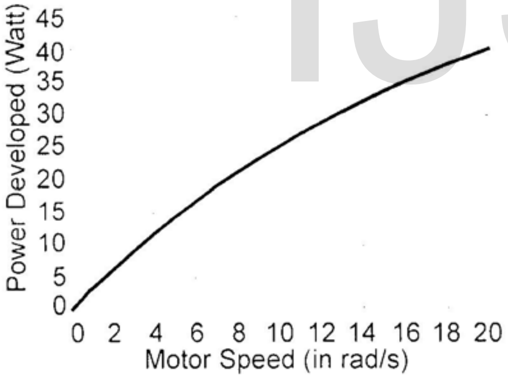


Fig. 18: Graph of Power versus Speed

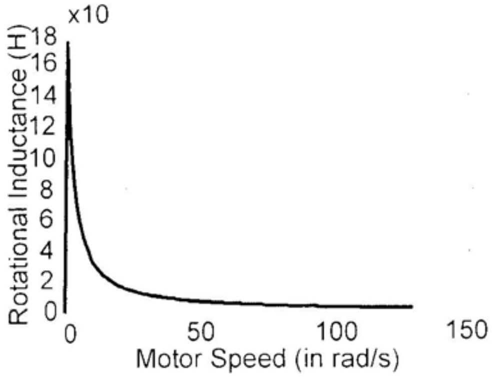


Fig.19 Graphs of G2 versus Speed

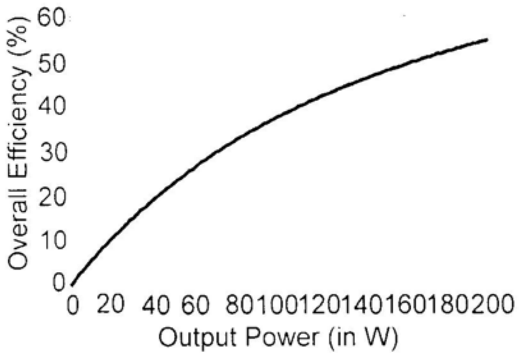


Fig. 20: Graph of Efficiency versus Power

The Motor Performance Parameters:

For the shunt-connected version –

The performance parameters of the shunt-connected dc motor shall be manually computed as presented below.

1. Maximum Starting Current ($I_{st(max)}$).

At starting E_r = 0Volt for absence of rotation [10], hence the armature circuit resistance R_a becomes directly paralleled to that of the field circuit, R_f. Consequently, the motor input current now assumes the maximum value,

$I_{st(m)} = V/\{R_aR_f/(R_a + R_f)\} = 220/\{2*202/(204)\} = 111$Amps.

2. Torque Developed.

Under full load, I_a = 11.4A as stipulated by the manufacturers. Thus,

$T_{dev} = GI_fI_a = 1.6*1.089*11.4 = 20$N-m

3. Angular Velocity & Power Converted or Developed.

$\omega_r = (V – I_aR_a)/[G_1I_f] = (220 – 11.4*2)/[1.6*1.089] = 113.2$ rad./s

$\therefore\ P_{dev} = \omega_r*T_{dev} = 113.2*20 = 2264$W

4. Total No-Load Copper Losses.

$P_{cu(o)} = I_{ao}^2*R_a + I_f^2*R_f = 0.491^2*2 + 1.089^2*202 = 240$W

5. Total Mechanical Losses.

$P_{mech} = P_{in(o)} – P_{cu(o)} = 348W – 240W = 108$W

5. Total Fixed or Constant Losses.

$P_{const} = P_{f(cu)} + P_{mech} = I_f^2*R_f + P_{mech} = 1.089^2*202 + 108 = 347.6$W

6. Total Variable Losses (i.e. Total Armature Copper or Load Losses)

$P_{vary} = P_{a(cu)} = I_a^2*R_a = 11.4^2*2 = 259.9$W

7. Total Machine Losses

$P_{loss} = P_{const} + P_{vary} = 347.6 + 259.9 = 607.5$W

8. Rated Output Power or Shaft Power.

$P_{out} = P_{dev} – P_{mech} = 2264 – 108 = 2156$W

9. Practical Input Power Requirement.

$P_{in} = P_{out} + P_{loss} = 2156 + 607.5 = 2764$W

10. Rated Output Torque

$T_{out} = P_{out}/\omega_r = 2156/113.2 = 19$N-m

11. Efficiency.

$\eta = P_{out}/P_{in} = (2156/2764)*100 = 78\%$

12. Speed Regulation.

$\omega_{reg} = \{[\omega_{ro} - \omega_r]/\omega_r\}*100\% = [(125.7 - 113.2)/113.2]*100 = 11\%$

13. Rated Starting Torque & Starting Current.

The rated starting torque has been given as 250 – 300% of the rated torque [12]. It follows that

$T_{st(rated)} = 2.5 - 3T_{out} = 47.5 - 57$ N-m

It is equally appropriate to stipulate that the rated starting current can be in the neighbourhood of 250 – 300% of the rated load current {although in [13] it is said to be up to $200\%I_{a(rated)}$}. That is

$I_{st(rated)} = 2.5 - 3I_{a(rated)} = 28.5 - 34.2$ A

For the series-connected version –

Concerning the performance parameters of the series-connected dc motor, the computations are equally manually executed as presented below. It is important to state here that, for reasons of safe operation, the full-load current under series condition cannot be more than $I_f = V/R_f = 1.089A$ or 1.09A being the maximum rating of the field winding; whereas, the armature winding rating is 11.4A (to which the field winding must not be subjected). However, computations are carried out with $I_f = 0.895A$ being the field current for the production of the motor nominal rated speed of 1500rpm, which is only slightly higher than 2 times the no-load current, under series operation.

1. Maximum Starting Current ($I_{st(m)}$).

Setting $E_r = 0$Volt at starting (as earlier explained), then R_a is directly in series with R_f. Consequently, the motor input current now assumes the maximum value,

$I_{st(m)} = V/(R_a + R_f)\} = 220/(2 + 202) = 1.08$Amps.

2. Torque Developed.

$T_{dev} = G_2I_fI_a = G_2I^2 = 2.8*0.895^2 = 2.24$N-m

3. Angular Velocity & Power Converted or Developed.

$\omega_r = \{V - I(R_a+R_f)\}/(G_2I) = \{220 - (0.895*204)\}/(2.8*0.895) = 14.93$ rad./s

$P_{dev} = \omega_r*T_{dev} = 14.93*2.24 = 33.44W$

4. Total No-Load Copper Losses

$P_{cu(o)} = I_o(R_a + R_f) = 0.4(2 + 202) = 81.6W$

5. Total Mechanical Losses

$P_{mech} = P_{in(o)} - P_{cu(o)} = 88 - 81.6 = 6.4W$

6. Total Fixed or Constant Losses.

$P_{const} = P_{mech} = 6.4W$

7. Total Variable Losses (i.e. Total Copper or Load Losses) .

$P_{vary} = P_{cu} = I^2*(R_a + R_f) = 0.895^2*(2 + 202) = 163.4W$

8. Total Machine Losses

$P_{loss} = P_{const} + P_{vary} = 6.4 + 163.4 = 169.8W$

9. Rated Output Power or Shaft Power.

$P_{out} = P_{dev} - P_{mech} = 33.44 - 6.4 = 27.04W$

10. Practical Input Power Requirement.

$P_{in} = P_{out} + P_{loss} = 27.04 + 169.8 = 196.84W$

11. Rated Output Torque

$T_{out} = P_{out}/\omega_r = 27.04/14.93 = 1.81$N-m

12. Efficiency.

$\eta = P_{out}/P_{in} = (27.04/196.84)*100 = 13.74\%$

13. Speed Regulation

$\omega_{reg} = \{[\omega_{ro} - \omega_r]/\omega_r\}*100\% = [(123.4 - 14.93)/14.93]*100 = 727\%$

Open-Circuit Characteristic (OCC) Plots –

The OCC's of the motor under both operational conditions were plotted for further analytical exercise. Tables 2(a) and 2(b) earlier given show the experimental data for the purpose; whilst Fig. 21 and 22 are the plotted OCC's.

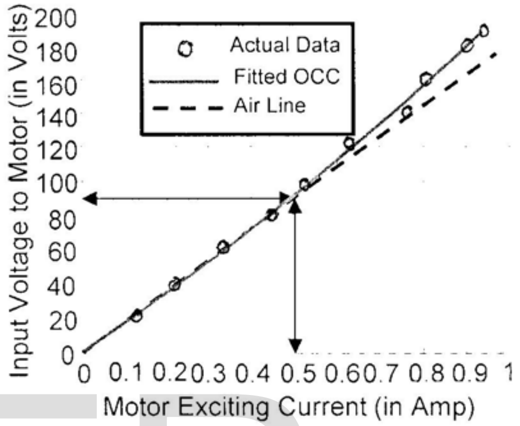


Fig. 21: Open-Circuit Characteristic (OCC) of the Test DC Motor under Shunt-Connected Operational Mode [where Air-Line Slope = 90/0.5 = 180Ω. Hence, input voltage = 162V for nominal rated exciting current of 0.895A or 0.9A approximately (for 1500rpm speed). However, on the OCC directly the input voltage required for this exciting current is 180V].

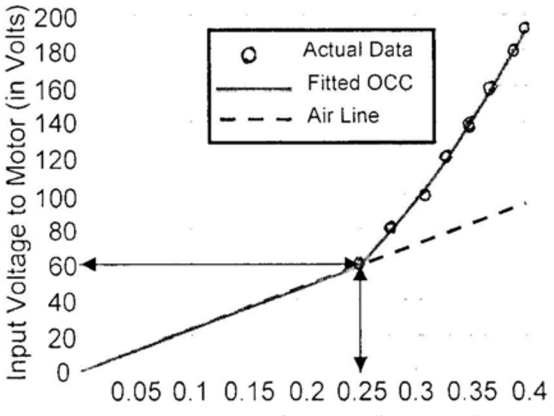


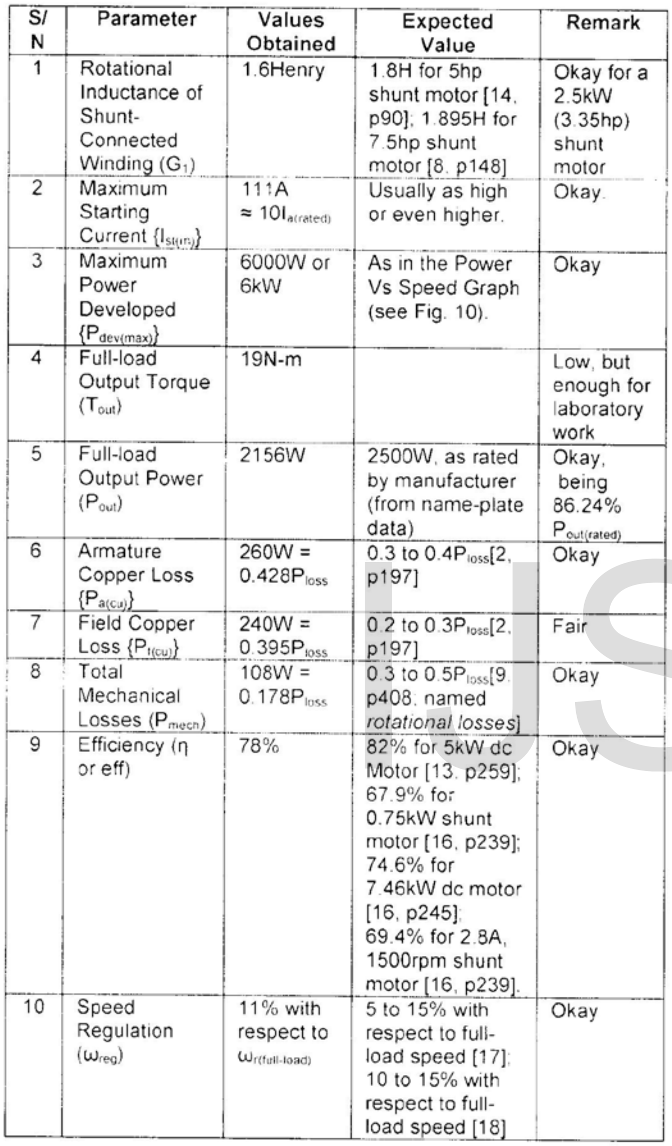
Fig. 22: Open-Circuit Characteristic (OCC) of the Test DC Motor under Series-Connected Operational Mode [where Air-Line Slope = 60/0.25 = 240Ω. Hence, input voltage = 216V for nominal rated exciting current of 0.895A or 0.9A approximately (for 1500rpm). However, on the OCC by extrapolation, the input voltage required for this exciting current will be 690V].

3.2 Discussion:

For the shunt-connected version –

A tabular discussion of results is provided in this work as presented in Table 4.

TABLE 4: Summary of Results and Analytical Submissions for the Shunt Version



S/ N	Parameter	Values Obtained	Expected Value	Remark
1	Rotational Inductance of Shunt-Connected Winding (G_1)	1.6Henry	1.8H for 5hp shunt motor [14, p90]; 1.895H for 7.5hp shunt motor [8, p148]	Okay for a 2.5kW (3.35hp) shunt motor
2	Maximum Starting Current {$I_{st(in)}$}	111A $\approx 10I_{a(rated)}$	Usually as high or even higher.	Okay.
3	Maximum Power Developed {$P_{dev(max)}$}	6000W or 6kW	As in the Power Vs Speed Graph (see Fig. 10).	Okay
4	Full-load Output Torque (T_{out})	19N-m		Low, but enough for laboratory work
5	Full-load Output Power (P_{out})	2156W	2500W, as rated by manufacturer (from name-plate data)	Okay, being 86.24% $P_{out(rated)}$
6	Armature Copper Loss {$P_{a(cu)}$}	260W = $0.428P_{loss}$	0.3 to $0.4P_{loss}$[2, p197]	Okay
7	Field Copper Loss {$P_{f(cu)}$}	240W = $0.395P_{loss}$	0.2 to $0.3P_{loss}$[2, p197]	Fair
8	Total Mechanical Losses (P_{mech})	108W = $0.178P_{loss}$	0.3 to $0.5P_{loss}$[9, p408, named *rotational losses*]	Okay
9	Efficiency (η or eff)	78%	82% for 5kW dc Motor [13, p259]; 67.9% for 0.75kW shunt motor [16, p239]; 74.6% for 7.46kW dc motor [16, p245]; 69.4% for 2.8A, 1500rpm shunt motor [16, p239].	Okay
10	Speed Regulation (ω_{reg})	11% with respect to $\omega_{r(full\text{-}load)}$	5 to 15% with respect to full-load speed [17]; 10 to 15% with respect to full-load speed [18]	Okay

For the series-connected version –

It is of great significance to state at this juncture that although the machine was designated for dual application, it can safely and practically and directly lend itself more for shunt operation than series operation. This is due to the very high field resistance that comparatively renders the total armature circuit resistance negligible as often the case and acceptable for shunt dc motors. Since, the field current is 1.09/0.7A for 1450/1550 rpm, it is obvious that the field current for the nominal or rated speed of 1500 rpm is 0.895A. This current was used as the full-load current under series operations; whilst the armature full-load current given as 11.4A was, of course, used as such for computations under shunt operations.

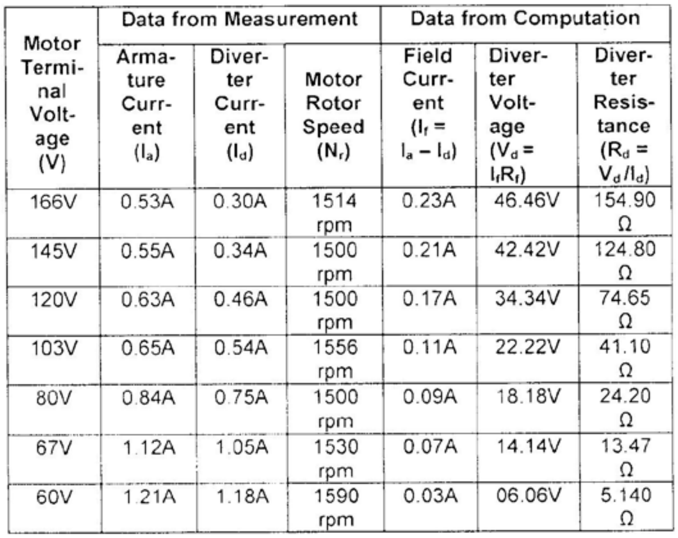
The high field resistance working in series with the armature circuit resistance explains why the losses totaled up to 169.8W for an input power of 196.8W (over 86% losses). It thus explains why only 33.44W of active power was developed or converted (being only 17% of input power). For the same reason, the speed regulation assumed an astronomical value of 727%. And being a function of the square of current, the torque developed (following the very low input current requirement) assumed an extra-low value of 2.24N-m, whilst the shaft or net output torque was 1.8N-m.

In terms of saturation property, it has been observed from the plotted OCC that the rated exciting field current for the nominal speed which is 0.9A approximately requires 216V on the air line for emergence, whilst it would require 690V on the OCC. Since the two voltage points also produce potential differences of 216V and 690V from the reference point, it follows from [19] that the motor exhibits a saturation factor of 690/216 = 3.19 p.u. (an extremely high value) under series operational condition. This is very much at variance with the 180/162 = 1.11 p.u. (considered as slight saturation value) under shunt operational condition.

Improvement of Machine Performance under Series Connection –

By the use of suitable field diverters the performance of the series-connected machine can be significantly improved. Field diverters are resistance units connected in parallel with the field circuit of a series motor for increase in speed even above nominal or rated speed [8], [20], [21]. Table 5 shows the result of such application as affecting the dc machine under investigation.

TABLE 5: Result of Increase in Motor No-Load Speed using Various Field Diverters



Motor Terminal Voltage (V)	Data from Measurement			Data from Computation		
	Armature Current (I_a)	Diverter Current (I_d)	Motor Rotor Speed (N_r)	Field Current ($I_f = I_a - I_d$)	Diverter Voltage ($V_d = I_fR_f$)	Diverter Resistance ($R_d = V_d/I_d$)
166V	0.53A	0.30A	1514 rpm	0.23A	46.46V	154.90 Ω
145V	0.55A	0.34A	1500 rpm	0.21A	42.42V	124.80 Ω
120V	0.63A	0.46A	1500 rpm	0.17A	34.34V	74.65 Ω
103V	0.65A	0.54A	1556 rpm	0.11A	22.22V	41.10 Ω
80V	0.84A	0.75A	1500 rpm	0.09A	18.18V	24.20 Ω
67V	1.12A	1.05A	1530 rpm	0.07A	14.14V	13.47 Ω
60V	1.21A	1.18A	1590 rpm	0.03A	06.06V	5.140 Ω

It is to be noted that as power developed, P_{dev}, is directly proportional to speed, increase in the rotor speed, N_r or ω_r, means an increase in the machine power developed, other advantages notwithstanding.

4 CONCLUSION AND RECOMMENDATION

4.1 Conclusion:

The objective of determining the rotational inductances of a laboratory dc motor has been accomplished under shunt- and series-connected versions of operation. The use of the same to generate and document the necessary performance parameters and graphs of the machine has much equally been realized as the ultimate goal. The machine proved itself capable of both laboratory and some industrial applications as a shunt-connected dc motor. But, it can only lend itself directly or unaided to some laboratory experiments under series-connected version of operation, such as an open-circuit characteristic (OCC) experiment.

4.2 Recommendation:

Although, additional cost inevitably comes into play with the application of field diverters, it is however obvious that provision shall have to be made for them if much gainful use is to be derived from the machine under series connection.

REFERENCES

[1] Mehala N. (2010): *Condition Monitoring & Fault Diagnosis of Induction Motor Using Motor Current Signature Analysis;* PhD Thesis, Electrical Engineering Department; National Institute of Technology, Kurukshetra, India; pp 10 – 13.

[2] Theraja B. L. (1997): *Fundamentals of Electrical Engineering and Electronics*, 28th Ed., New Delhi, S. Chand & Co. Limited; p.217.

[3] Bhattacharya S. K. (1998): *Electrical Machines*, 2nd Ed., New Delhi, Tata McGraw-Hill Publishing Company Limited; p.16.

[4] Mishra G. K., Pandey A. K. & Maurya A. (2014): *Combined Armature and Field Speed Control of DC Motor for Efficiency Enhancement*; SSRG International Journal of Electrical and Electronics Engineering (SSRG-IJEEE); Vol. 1, Issue 6; pp.34–39.

[5] Oghuvwu D. et. al. (2016): *Design and Construction of 10A, 415V, 3-Phase Inductive Load Bank;* HND Students' Final Year Project Work Report; Department of Electrical/Electronic Engineering Technology; Auchi Polytechnic, Auchi, Nigeria; p.12,13.

[6] DC Motors: https://www.pc-control.co.uk/dc-motors.htm (8/9/2016)

[7] Say M. G. & Taylor E. O. (1980): *Direct Current Machine*, London, Pitman Publishing Limited; p.1, 256-258.

[8] Daniels A. R. (1976): *Introduction to Electrical Machines*, Maiden Ed., London, Macmillan Press Limited; p.137, 148.

[9] Gupta J. B. (2005): *Theory & Performance of Electrical Machines*; 14th Ed.; Nai Sarak, Delhi; S. K. Kataria & Sons; p.292, 408-409.

[10] vlab.ee.nus.edu.sg/~bmchen/courses/EG1108_DCmotors.p df p.11

[11] Enyong P. M. (2015): *Pre-commissioning Tests and Functionality Assessment of a Bulk Power Transformer;* International Journal of Engineering Innovation & Research; Vol. 4, Issue 3; pp. 510–519.

[12] Chapter 3: AC and DC Motors – DC Motors: General Principles of Operation; p.83 – 88; www.globalspec.com

[13] Mittle V. N. & Mittal A. (1996): *Design of Electrical Machines*, 4th Ed., Nai Sarak, Delhi, Standard Publishers Distributors; p.81.

[14] Krause P. C. (1986): *Analysis of Electric Machinery*; New York; McGraw-Hill Book Publishing Co. Ltd.; p.90.

[15] Craig Kevin (--): *Brushed Direct-Current Motors*; Mechanical Engineering Dept.; Rensselaer Polytechnic Institute; p.89, 102. *Multimechatronics.com/images/uploads/mech_n/Brushed_DC_Motors.pdf*

[16] Mehta V. K. and Mehta Rohit (2009): *Principles of Electrical Machines*, 2nd Ed., New Delhi, S. Chand & Company Limited; p.239, 245.

[17] Daware K. (2014): *Characteristics of DC Motors*; Kiran Daware DC Machines 6 Comment Tweet; www.electricaleasy.com/2014/7/characteristics-of-dc-motors.html

[18] Theodore Wildi (2004): *Electrical Machines, Drives and Power System;* 4th Ed, Prentice Hall PTR; DC_Motor_Calculations_2004.pdf (part 2).

[19] Enyong P. M. (2015): *Experimental Determination of Magnetic Saturation Factor for A Better Survey of A Single-Phase Induction Motor Performance;* International Journal of Emerging Technology & Research; Vol. 2, Issue 3; pp.88-96.

[20] Sharma S., Oberoi S. S. & Nair S. (2014): *Speed Control Method of DC Series Motor; International Journal of Innovative Research in Technology (IJIRT);*Vol. 1, Issue 6; pp.1450-1453.

[21] http://uotechnology.edu.iq/dep-eee/lectures/2nd/Electrical; (20/12/2016); 17 pages.

ENYONG, Peter Michael is a Chief Lecturer in the Department of Electrical/Electronic Engineering of Auchi Polytechnic, Auchi, Nigeria. He holds a B.Eng. (Electrical/Electronic Engineering) degree from University of Nigeria, Nsukka; an M.Eng. (Power/Machines) degree and a Ph. D. (Power/Machines) both from the University of Benin, Benin-City, Nigeria. He is a father of four boys who enjoys his marital life; a lover of reading, writing and publishing.

OBAITAN, Evaristus Bola is a Principal Lecturer in the Department of Electrical/Electronic Engineering of Auchi Polytechnic, Auchi, Nigeria. He is a holder of B.Eng. (Electrical/Electronic Engineering) and M.Eng. (Power/Machines) degrees both from the University of Benin, Benin-City, Nigeria. He also possesses a considerable on-the-job cognate experience in the Steel and Oil Industries. He is a happily married man with children, who is currently pursuing his Ph.D programme in Power/Machines.