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Numerical Investigation of Asynchronous Machines: A Comparism of Experimental With Computer Simulation Approaches in the Determination of Per Phase Machines Parameters

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Abstract

Performance analysis of a three-phase, star/delta connected, 1.1kW, 380V, 50Hz, 2.6A rated current having inertia 0.0023Kg/m^2 was carried out in this work. This was realized through experimental test such as; dc test, block rotor test, no-load test and load test. Using the machine parameters obtained from the test results, the simulation was carried out machine parameters were used in MATLAB/ SIMULINK ENVIRONMENT. Operating characteristics such as; torque/speed, current/speed, speed/power, torque/power, current/power and torque/slip using parameters from the experimental tests were compared with the simulated. Results obtained from the correlation showed no remarkable difference. The Investigation revealed that the aggregate time involve in the physical experiment, laborious computing and plotting of the relationships with the swift and reliable output from the simulations, simulation mode outstand the analytical method of demonstrating machines performance characteristics.

Keywords: Performance, Operating, Characteristics, Analysis, Torque, Slip, Speed, Power, Efficiency.

1. Introduction

In most industrial and agro-allied drives, electronic/electrical equipment/devices, the use of electrical machines stands out. In this work the concern is dynamic rotary electric motors in operation. Based on the speed at which electromagnet torque is developed asynchronous machines compared to synchronous machines is a variable sped device which must slip in order to generate torque. It ranges from very small fractional horse power to very large sizes, Depending on the mode of supply it can be operated as a direct current (dc) or alternating current (ac) motor.

Standard formulas for determining machines parametric values are in many books thus the motivation of this research work geared at attaining the following:

- Based on the experimental results of the designed and constructed motor compute machine parameters, determine its starting, no-load and full-load characteristics;
- Using the machine dimensions and assumed values in simulation the conceived new machine performance characteristics can be analyzed, pre-determined and improved upon before further construction;
- Design more efficient machines at minimal cost;
- When the machine parametric equations are simulated, any deficiency in its expected performance are eliminated or minimized before the actual construction.

Every manufactured electric motor have structured features such as; open. Semi-closed or closed slot, ventilated or pipe ventilated etc. backup by the technological know-how of the designer and outlined performance characteristic to be achieved. The electromagnetic compatibility (EMC) of the load the device is subjected allows the establishing of the maximum perturbations which the different types of electrical devices can accept without anomalous functioning [1]. The Computer simulation was carried out using MATLAB power system block set / SIMULINK software VERSION 7.5.0(R2007b). It provides designed experimental models of power system equipment such as; induction motors, transformers, etc., test. The measured values enabled computation of the machine parameters such as torque, reactive and active power, angular speed etc., and performance characteristics for comparison at varied voltages and frequencies. Because of limitation of pages it will not be possible to include and discuss the circuits connection and simulation techniques employed in this work. Section two of this work presents the machine features and operating characteristics, the experimental and simulation results and analysis are presented in section 3. The conclusion of this work is in section 4.

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Symbols

ω = angular speed of magnetic flux, rad/sec
Δ_T = incremental time
$\Phi_{\max}$ = maximum magnetic flux, Webbers
η = efficiency of the motor @ each load level
f_r = frequency of operation, Hz
I_{Av} = average per current, amps
$I_{R,Y,B}$ = phases current, amps
J = moment of initial, kg/m ^{2}
K_p = pitch factor
K_d = distribution winding factor
K, K_f = machine constants
L_1,m = stator and core inductances respectively, henrys
M = mass of rotor, kg
ω_m = angular frequency, rad/sec
n = rotor mass angular speed, rad/sec
N_{syn} = synchronous speed, rpm
N_r = rotor shaft speed at each load level, rpm
P = no. of poles
$P_{3\text{-}\phi}$ = three – phase power, watts
P_{in} = total power input at each load level, watts
$P_{out,W}$ = output power at each load level, watts
P_R = measured power per phase, watts
P_r, Q_r = real and reactive power per phase, watts, var respectively
P_{rot} = rotational losses
P_{SCL} = stator copper losses
r = radius of rotor, cm
R_2^1 = rotor resistance referred to the stator, ohms
R_1 = stator resistance, ohms
R_c = copper losses resistance, ohms
t = time of processing, sec
$T_{m,e,l}$ = motor torques, N-m
V_r = velocity of rotor, m/sec
V_2 = induced voltage, volts
V_L = phases voltage (line to line voltage), volts
V_p, V_1 = phase voltage (phase to neutral), volts
X_1, X_2 = stator and rotor reactance respectively, ohms
X_m = = magnetizing reactance, ohms
Z_t = total number of armature conductors in series/phase

2. Rotating electrical machines features and operational characteristics

Electrical machines are electromagnetic devices in nature that work on the principles of Faraday's Law of electromagnetic induction and Lenz's Law of interaction. They convert energy from one form to another depending on the mode of operation. Apart from static electrical machines like transformers, synchronous condenser, reactors, the others consist of three main parts, namely, the stator, the rotor, and the annular airgap. The operational characteristics of synchronous and asynchronous machines are briefly presented in this work. If the produced torque is larger than any load torque, the rotor begins to turn. As the rotor accelerates, the speed difference between the rotor and armatures field is reduced. This reduced speed difference (or slip) causes the induced rotor voltage to be reduced, the rotor current to be reduced, the rotor flux to be reduced, and the

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torque produced by the machine to be reduced. Eventually, the torque produced by the motor equals the torque demanded by the load, and the motor settles to equilibrium rotor speed less than synchronous speed since there must be a slip to produced torque. At full-load motor runs at constant-speed. The stable operation of an induction motor lies over the linear portion of the plot, and its slope depends mainly on the rotor resistance, the higher the resistance, the sharper the slope.

2.1. Equivalent circuit of asynchronous machines

The stator design determines the induction motor rated speed and most of the full load, full speed characteristics, while the rotor design determines the starting characteristics and the annular airgap design determines the magnetic reluctance and the relative motion [2]. Figure1 illustrates the machine equivalent circuit, from which the machine operating characteristics can be evaluated.

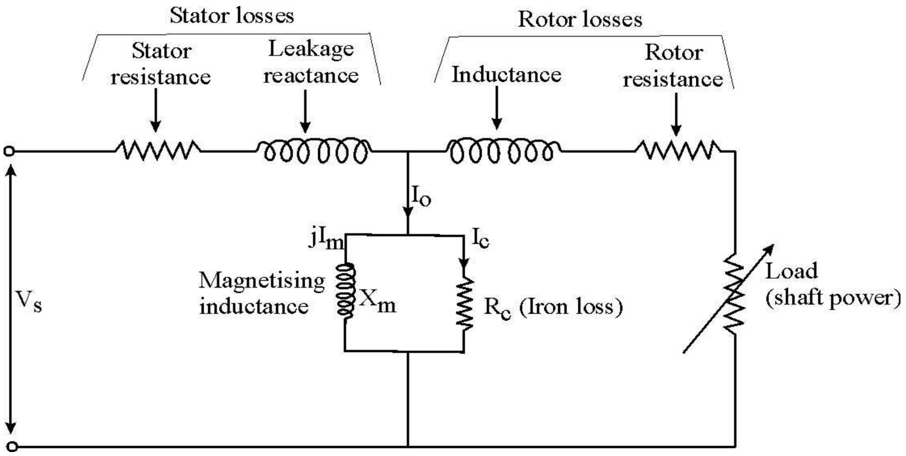

Figure1. Equivalent circuit of induction motor

In the equivalent circuit (Figure1) the magnetizing current (I_m) and iron loss components are voltage dependent and not load dependent. The full voltage-starting current of a particular rotor is voltage and speed dependent, but not load dependent. The magnetizing current varies depending on the design of the rotor, (small motors, I_m is as high as 60%, for large 2 pole motors, I_m is as low as 25% of the load current respectively) since the iron is typically near saturation at the design voltage, the iron loss and magnetizing current do not vary linearly with voltage, but friction and windage losses increase significantly at higher speeds. The stator of an induction motor is similar to that of a synchronous alternator and motor, and in the case of a machine with three-phase supply, a symmetrical rotating magnetic flux is produced. The air gap between the rotor and the stator is uniform and made as small as is mechanically possible for a uniformly distributed magnetic flux and the e.m.f generated in a rotor conductor is a maximum in the region of maximum flux density. The revolving magnetic flux is rotating synchronously relative to the stator (i.e. stationary space) but at slip relative to the rotor, sometimes $N_s - N_r$ is called the slip speed. The term "slip" is descriptive of the way in which the rotor "slips back" from synchronism [3]. For torque varying between zero (i.e. $N_s = N_r$) and the full-load value, the slip is practically proportional to the torque [4]. The locked rotor torque (LRT), (approximately equal to 1.5 times the rated torque) and the locked rotor current (LRC) (which is very high) are functions of the terminal voltage of the motor and the motor rotor design. Since torque developed in machines is directly proportional to I^2R of the rotor, the starting efficiency of the motor indicates the ability of the motor to convert amps into Newton meters, which is very useful when comparing induction motors. Mathematically [2];

$$\text{Starting Efficiency} = \frac{\text{Locked Rotor Torque}}{\text{Locked Rotor current}} \equiv \left[\frac{\%\text{ of FLT}}{\%\text{ of FLC}}\right] \qquad (1)$$

From this expression it implies that if the start voltage(V_T) applied to a motor is halved, the starting torque will be a quarter of rated voltage, also if V_T is 1/3, it yields $^1/_9$ start torque, the efficiency is highest at ¾ load and varies from less than 60%. The running actual full load slip, at a speed determined by the number of stator poles, of induction motor is dependent on the motor design (and it is usually less than 5%). This is the same as the speed of the rotor in a synchronous generator with the same number of poles and producing the same frequency. The back emf generated in the stator or air gap voltage is;

$$E_b = 2.22K_dK_p Z_t f_r \Phi_{\text{max.}} \qquad (2)$$

While the rotor emf generated per phase, considering the per unit slip s, is given by the relation;

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$$E_r = 2.22K_dK_p Z_t f_r \Phi_{max} \qquad (3)$$

The speed at which the rotor conductors are cut by the rotating magnetic flux is related to the emf by frequency of rotor emf $(f_r) = (N_{syn} - N_r) P = SN_{syn} P = Sf$ (4)

Equation 4 gives the frequency of the rotor current (I_o) in terms of percent slip [5]. Consequently the speed of the rotor ampere-turns relative to the stator core is;

$$= (N_{syn} - N_r) + N_r = N_{syn,}\ \text{rev/secs} \qquad (5)$$

The percentage slip varies with load on motor shaft, as the load increases. In this respect the poly-phase induction motor can be regarded as being equivalent to transformer having ac air gap separating the iron portions of the magnetic circuit carrying the primary and secondary windings [3]. Generally, the torque developed is given by;

$$T \propto \frac{sE_b{}^2 R_r}{R_r{}^2 + (sX_{l_r})^2}; \quad \propto \frac{s\Phi_{max}{}^2 R_r}{R_r{}^2 + (sX_{l_r})^2}; \quad \propto \frac{Ks\Phi_{max}{}^2}{R_r{}^2 + (sX_{l_r})^2} \qquad (6)$$

and

$$\frac{\text{operating torque at any slip, s}}{\text{maximum torque (Breakdown torque)}} = \frac{2as}{a^2 + s^2} \qquad (7)$$

Where, $a = \frac{R_r}{X_r}$

The parameters under two different load conditions are related by the equation [6];

$$S_2 = S_1\left(\frac{T_2}{T_1}\right)\frac{R_2}{R_1}\left(\frac{V_1}{V_2}\right)^2 \qquad (8)$$

Such that T_2 must not be greater than $T_1\left(\frac{V_1}{V_2}\right)^2$ for equation 8 to yield accuracy better than 5% which is sufficient for all practical purpose. The torque output and power delivered by an induction motor varies as the motor speed changes, but at synchronous speed no power is delivered at all [7]. Figure 2 shows the torque-speed characteristics of asynchronous machines [2, 8], while Figures 3a-d shows the plots of a redesigned single phase squirrel-cage induction motor from a burnt out three-phase induction motor operated as induction generator [9].

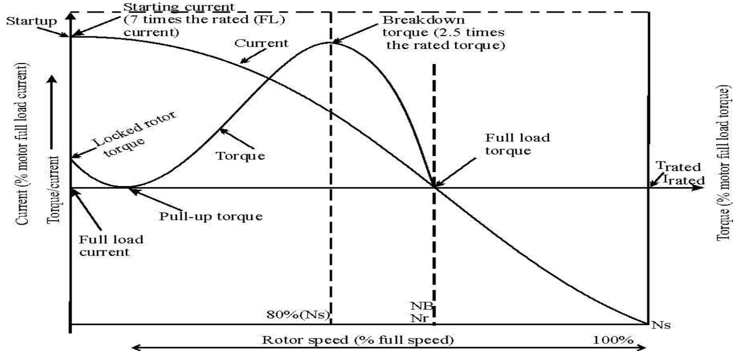

Figure 2. Torque-speed characteristics of induction motors.

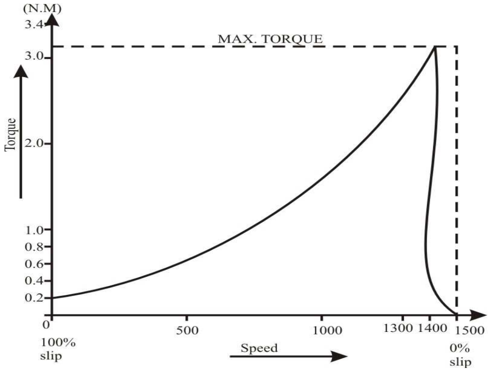

Figure 3.a Plot of torque against speed of the redesigned single phase squirrel cage induction motor operated as SEIG

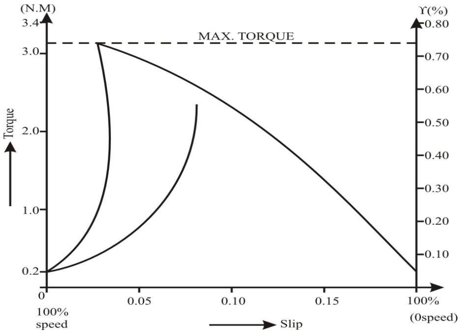

Figure 3.b Plot of torque against slip and efficiency vs slip of the redesigned single phase squirrel cage induction motor operated as SEIG

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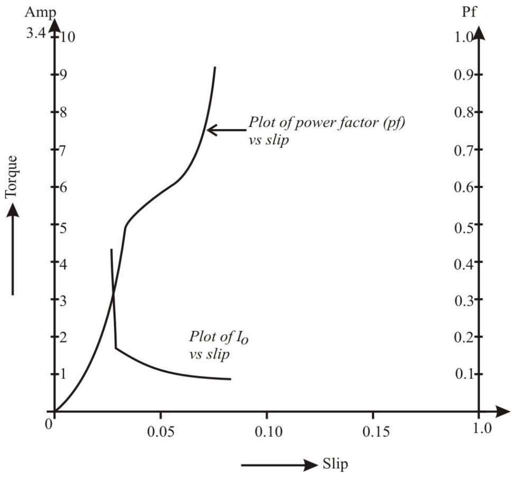

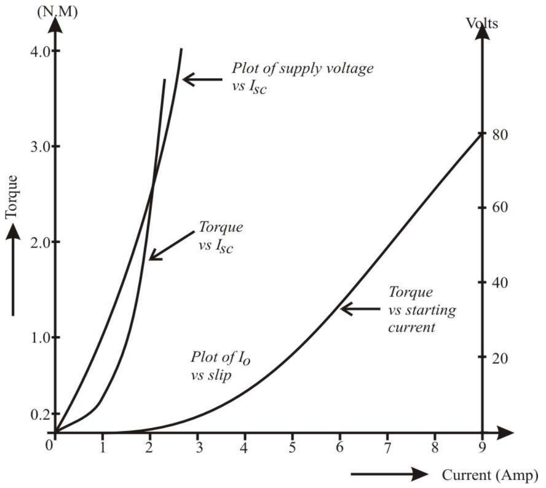

Figure 3.c Plot of no-load current (Io) against slip and power factor vs slip of the redesigned single phase squirrel cage induction motor operated as SEIG

Figure 3.d Plot of torque against short circuit current and starting current and supply voltage against Isc of the redesigned single phase squirrel cage induction motor operated as SEIG

From the speed-torque characteristics, torque is highly non-linear as the speed varies. The torque developed is directly proportional to the rotating magnetic field produced by the stator and the frequency. The applied stator voltage is related to the magnetic flux linkage and the rotating speed by this expression;

$$\text{Stator voltage (V)} = E_b \ \alpha \ (\text{stator flux } (\Phi_{\max}) \text{ x Angular velocity } (\omega))]$$

$$= \Phi_{\max} \text{ x } 2\pi f_r K_f \qquad (9)$$

From equation 9, the rotating magnetic flux is the ratio of the stator terminal voltage and the angular frequency, a constant which is the most common speed control theory of the induction motor [8]; this shows the major effect of change in supply frequency on an electric motors speed. Thus reduction in frequency (i.e. frequency control), we can obtain a large torque from zero to full speed with reduced current and this enables regenerative braking of motor. The nominal (operating) speed of induction motor is based on the line frequency and their individual “slip factor”. Operating with the positive slip, the motor can generate the same amount of power it would have used as motor (operating with the negative slip) [10]. In this light, Table 1 shows induction motors performance in terms of design features. It is important to also note that the centrifugal force on a high speed rotor is given by the expression [3, 11, 12]**;**

$$\text{Centrifugal force on rotor} = \frac{MV_r^{\ 2}}{n} \text{ , KN} \qquad (10)$$

Table I: Induction motor performance in terms of design features [2]

Design Type A	**Parameter Value**	**Special Action**
Shallow bar rotor	High starting current, 850% of FLC	Low starting Torque (120%) of FLT
Deeper bar rotor	Medium starting current 650% FLC	Medium starting Torque (180%) of FLT
	Low starting current	High starting Torque
	Large inductance (X_s), high speed	Low magnetizing current (I_o), low iron Loss, high power factor up to 0.9, efficiency > 92%
	Small Inductance (X_s), low speed	High magnetizing current (I_o), high iron Loss, power factor up to 0.5, efficiency < 60%
	Small motors (1KW and above)	Full-load slips (about 5%)
	Large motors (100KW and above)	Full-load slips (about 1%)

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2.2. Effect of Change in Speed

The change in speed either increases or decreases (Δn) in the application of electrical machines is related by [12];

$$\Delta n = \frac{9.55T_t\ \Delta t}{J} = 9.55(T_m - T_L)\ \frac{\Delta T}{J}\ \ldots\ldots\ldots\ldots \qquad 11$$

When T_m is equal to $T_{L,}$ the motor/load system in effect is in a state of dynamic equilibrium. From equation 11, the speed may be zero, clockwise or counter clockwise. The relationship between the power developed by electric motor and the motor torque is given by the expression;

$$\text{Po} = \frac{nT_m}{9.55} \equiv \frac{W}{t} Joules/\sec(Watt)\ \ldots\ldots\ldots\ldots\ldots \qquad 12$$

In a mechanically coupled system, when the torque (T_m) developed by a motor acts in the same direction as the speed (N_r), the motor delivers power to the load. For all other conditions, the motor receives power from the load. This occurs for brief periods in electric trains and electric hoists, wire–drawing machines. Concluding this section, Table II highlights the capability and limitations of practical use of synchronous and asynchronous motors

Table II: Comparisons between synchronous and asynchronous Motors [13]

	Synchronous Motor	**Induction Motor**
1.	Not self-starting	Self-starting
2.	The average speed of the synchronous motor is always synchronous and is independent of load	The induction motor has a normal speed less than that of synchronous: and its speed decrease as the load applied by it increases
3.	The motor can be operated at all power factors whether lagging or leading	The motor operates at only lagging power factors and its power cannot be efficiently controlled
4.	No question of speed control over the controllable range	Speed can be controlled to small limits and can withstand 100% over speed
5.	In addition to the motor being used for mechanical outputs, it has a better industrial application being used for improvement of power factor, in which case it is called as a synchronous condenser	The induction motor application is limited to the supply of mechanical load
6.	The motor requires a d.c. exciter	No exciter is required
7.	The motor is costlier to manufacturer	The motor is much cheaper to manufacture so it is a popular machine drive
8.	Some arrangement must be made for Starting and synchronizing the motor	Robust, simpler, reliable, rugged, requires little maintenance
9.	The lost/KW is generally higher than that of an induction motor	Can be used as "stand-alone" or "self excited". Induction generator or motor generators
10		Reducing voltage frequency we can obtain a larger torque with a reduced current

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11		Permits economy regenerative braking of the motor
12		Reduce voltage reduces the locked rotor current
13		Develop high torque from zero to full speed

3. Experimental/Simulation Techniques

The usual experimental work benches for open circuit, short circuit and load tests were used in this work, while for the simulation the following steps in MATLAB environment were used:

Step 1: Click on the Standard Tools bar after loading
Step 2: Double click on Simulink Icon
Step 3: Takes you to MATLAB Simulink Library
Step 4: Go To Sim Power Systems and Double click on it and it takes you to Sub-Library under Power Systems
Step 5: Open to pick the required block for the analysis
Step 6: Right click on the Symbol or Block set required + click on Add to untitled model for a new model
Step 7: To connect all the Blocks start joining
Step 8: For Machine measurement Properties, Right click on it + click on Machine Properties or Block Properties
Step 9: Select the desired Machine Parameters Values
Step 10: Run by clicking the Start Simulation Button.

3.1 Results

The various test results and the computed machine parameters from both the laboratory experiment and simulations are presented in Tables III to VIII. While some of the motor operating performance characteristics are illustrated in figures 4 to 6[**14, 15, 16, 17**].

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Table III: Dc resistance test and blocked rotor test results

Dc Test		Blocked rotor test												
Stator winding resistance, Roc (ohms)	Ac, Resistance R_1 (ohms)	V_L (Volts)	V_P (Volts)	$P_{3-\phi}$ (Watts)	P_R (Watts)	I_R (Amp)	I_Y (Amp)	I_B (Amp)	I_{AV} (Amp)	R_{eq} (ohms)	Z_{eq} (ohms)	X_{eq} (ohms)	$X_1(=X^1_2)$ (ohms)	R^1_2 (ohms)
10.10	11.60	120.00	69.30	400.00	133.33	2.50	2.50	2.70	2.6	19.72	26.65	17.92	8.96	8.12

Table IV: No - load test results

V_L (volts)	Vp (Volts)	$P_{3-\phi}$ (Watts)	I_R (Amp)	I_y (Amp)	I_B (Amp)	I_{AV} (Amp)	Pp (watts)	Iron loss Pc (watts)	Back emf E_b (watts)	Power factor co6 ϕ	Copper loss resistance Rc (ohms)	I_C (Amp)	Magneti-sing current Im (Amps)	Magnet Resistance Xm (ohms)	Lm (mH)	Stator Induc-tance (mH)
380.00	219.40	360.00	1.00	1.10	1.00	1.03	120	107.70	205.00	0.53	390.00	0.53	0.88	233.00	742.00	29.00

Table V: Blocked rotor simulation dc test results

S/N	Test frequency (H_Z)	V_R rms (Volt)	I_R (Amp)	P_R (Watt)	Q_R (Var)	ω_m (Rad/s)	R_{LR} (ohms)	X^1_{LR} (ohms)	X_{LR} (ohms)	$R_2(=R_{LR}-R_1)$ (ohms)	$X_1(=X_2)$ (ohms)	% error in experimented $X_1(=X_2)$	V_{DC}. (Volt)	I_{DC} (Amp)	R_1 (ohms)
1	40.00	64.65	2.60	140.90	101.70	1.250	20.84	15.00	18.75				105.90	4.56	11.60
2	50.00	71.68	2.60	130.50	126.40	1.018	19.30	18.70	18.70						
3	60.00	75.22	2.60	130.80	146.20	0.807	19.35	21.63	18.00						
4	Average						19.83	18.44	18.48	8.20	9.24	2.60			

Table VI: No - load simulation result

V_R (volts)	V_Y (volts)	V_B (volts)	I_R (Amps)	I_Y (Amps)	I_B (Amps)	P_R (Watt)	Q_R (Var)	Te (Nm)	ωm (rad/S)	$Xm+X_1$ (ohms)	Xm (ohms)	I_{AV} (Amps)	X_1 (ohms)	P_3-ϕ (watt)	P_{SCL} (watt)	P_{rot} (watt)	Starting current I_s (Amp)
220	220	220	0.922	0.925	0.925	56.23	194.69	0.895	155.70	240.00	230.76	0.92	9.24	169.00	29.46	139.54	7.20

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Table VII: Machine equivalent circuit parameters with corresponding errors

Parameters	R_1 (ohms)	R^1_2 (ohms)	X_1 (ohms)	X_2 (ohms)	X_m (ohms)
Experimental calculated values	11.60	8.12	8.96	8.96	233
Simulation values	11.60	8.20	9.24	9.24	231
Percentage error	0.000	0.935	2.600	2.600	0.858

Table VIII: Load test simulation result

Mechanical load Torque Tm (N_m)	V_{Rrms} volt	I_R (Amp)	P_R (watt)	Q_R (var)	ω_m (rad/s)	P out ($T_m \omega_m$) (watt)	Pin (=3P_R) (Watt)	N_R (=$W_m/2\pi$) (rpm)	Efficiency (η) (%)	(Slip(=s) (1500-N_R)/1500
5	220	1.85	352.40	213.00	146.50	732.50	1057.20	1398.97	69.29	0.067
6	220	2.14	412.40	226.90	144.10	864.60	1237.20	1376.05	69.88	0.082
7	220	2.46	486.10	245.70	141.50	990.50	1459.30	1351.22	67.85	0.099
8	220	2.80	550.60	270.40	138.50	1108.00	1651.80	1322.58	67.08	0.118
9	220	3.19	637.40	303.00	134.90	1214.10	1912.20	1288.20	63.49	0.141
10	220	3.62	719.80	346.50	130.60	1306.00	2159.40	1247.14	60.48	0.169
11	220	10.05	1282.00	1820.00	-1388.00	-15268.00	3846.00	-13252.70	-397.00	8.195
12	220	10.07	1269.00	1830.00	-1604.00	-19248.00	3807.00	-15315.10	-506.00	9.342
13	220	10.10	1283.00	1836.00	-1797.00	-23387.00	3849.00	-1716.90	-608.00	10.376
14	220	10.10	1276.00	1841.00	-1985.00	-27790.00	3828.00	-18952.90	-726.00	11.363
15	220	10.14	1239.00	1845.00	2165.00	-32475.00	3717.00	-20691.50	-874.00	12.329

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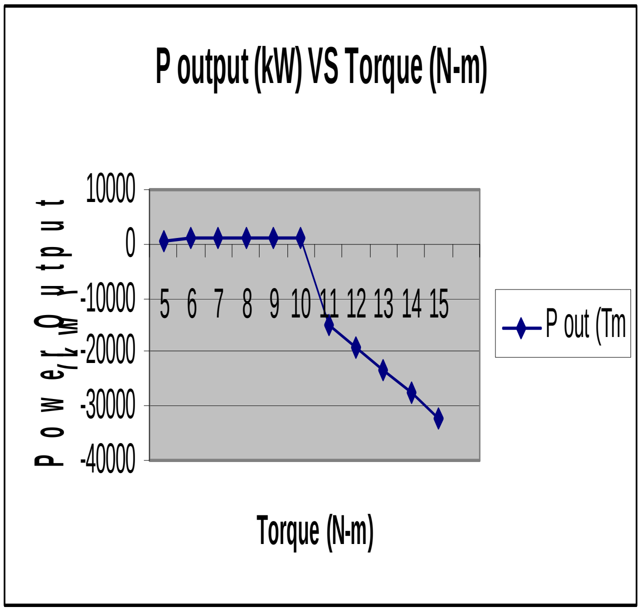

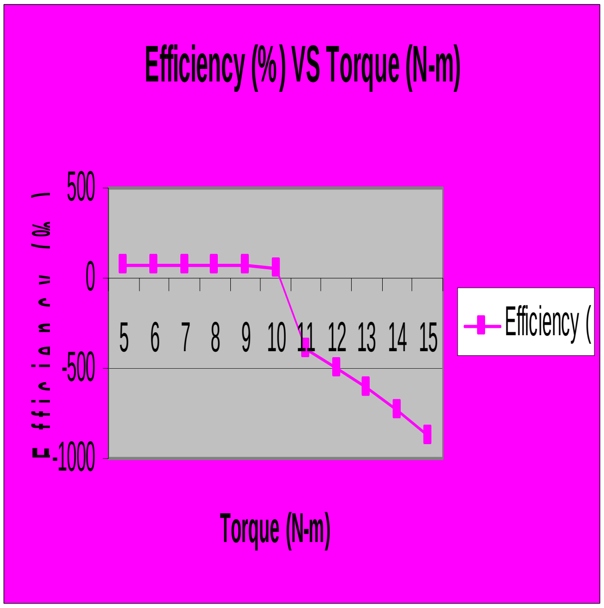

Figure4 the plot of available power against shaft torque

Figure5 the motor efficiency against

torque

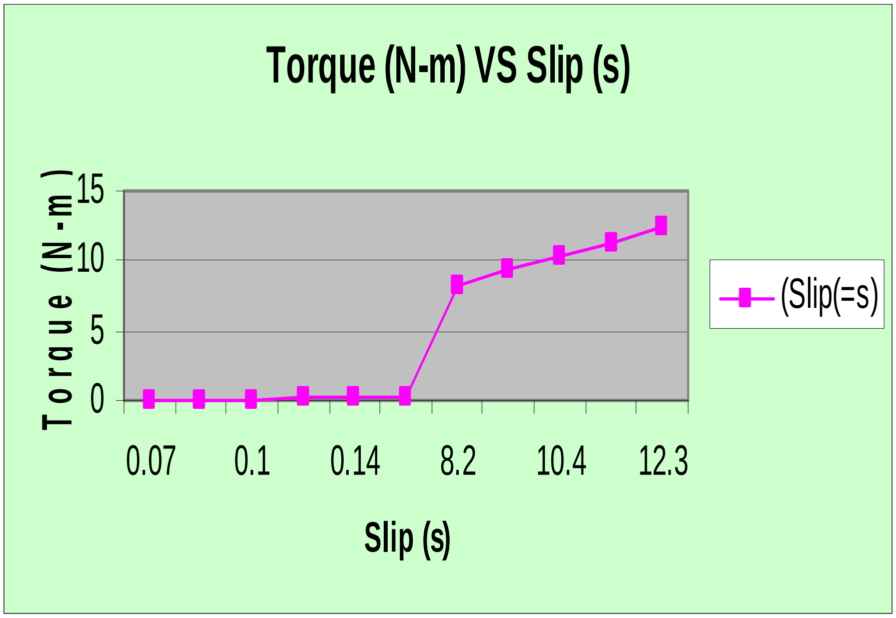

Figure6 the motor shaft torque against slip

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3.2 Results analysis

Depending on the motor behavioral pattern on loading conditions one wish to analysis, values measured and computed presented in Tables III to VIII can be plotted as desired. Due to constraint in number of pages some plots of the simulated blocked rotor results are shown in figures4 to 6. The figures buttress the facts that as the load torque demand on the motor increases the efficiency decreases, while when the direction of power flow reverses the asynchronous machines performed as induction generators [13]. The stator and rotor leakage reactance's error is negligible, therefore simulation models can be used to accurately predict asynchronous motor equivalent circuit parameters for determining its performance characteristics such as; the machine capability to with stand the supply voltage and the corresponding output performance. Analyses of the wave forms and plots show that the experimental results and simulated results buttress the theories and fundamental principles governing the operation of electrical machines. The negative values in Table VIII indicate maximum torque the machine can be subjected to under different loading conditions.

4 Conclusion

The performance analysis of an asynchronous machine based on experimental and computer simulation modes have been successfully investigated in this work. The percentage errors shown in Table VII attributable to equipment/instrument, computation and human errors shows that the simulation modes are based on the same principles that governors laboratorry experiments. The negative values recorded in Table VIII points the fact that machines has the maximum limit at which loads can be subjected to it, otherwise it runs into saturation region of the magnetic flux density/ magnetic flux intensity (B/H) curve and this can damage the machine if it can not pull-out of torque. The waveforms displayable in the simulated test clearly show the performance characteristics of the machine, thus represents the physical behavioral pattern inside the machine under the different loading conditions. The speed, accuracy and easy of interpretation of the simulated results is an acknowledgeable breakthrough in all field of study. Researches of this nature helps students and operators understanding to handle electrical machines properly, in the development of application software's and reduces the number break down of measuring instruments as experienced in most laboratories that often results in frustrations and dissatisfactions due to poor funding by concerned bodies.

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