Electrical and Computer Engineering Department

Electrical Machines LAB (ENEE3101)

Report on Experiment #5

Synchronous Motors (SM) and Slip Ring Motors

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Abstract

The aim of this experiment, is to help us understand the behavior of the synchronous motor and the induction motor, and how to operate both, also understand the load characteristics and the motor's efficiency, how the synchronous motor can work as a phase shifter, while the induction motor rotary transformer.

Equipment List:

Device Name	# Of the device
1 multi-function machine 0.3	732 28
1 machine test system	731 989
1 CBM 10 computer-based analysis of electrical machines, V.5	728 421
1 three-phase supply unit with FCCB	726 75
1 three pole on/off switch	731 42
1 motor protection switch, 1 ... 1.6 A	732 14
1 Extremely low DC voltage power supply	725 352
1 DC voltage power supply	725 852
1 power factor meter	727 12
2 RMS meters	727 10
1 Rotor starter resistor	732 29

Table 1 List of Equipment Used

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Theory

Synchronous Motor

A not self-starting motor that converts electrical power into mechanical work, and runs on a constant speed which is known as (Synchronous speed).

To operate the synchronous motor, there is a magnetic field on the rotor winding produced by a DC current applied to p-poles field windings on the rotor B_R, and a three-phase current which produce a uniform rotating magnetic field B_s, both these magnetic fields tend to align with each other.[1]

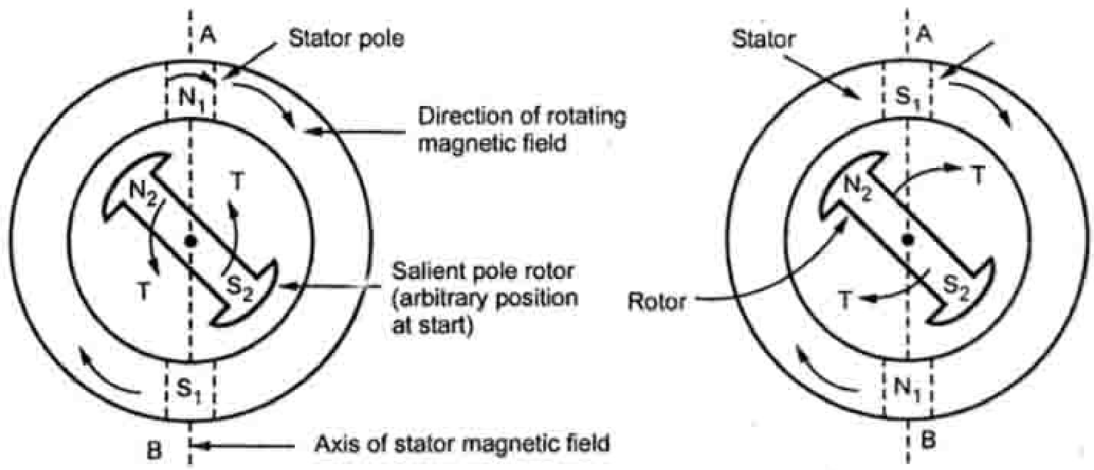

Figure 1 Principle of working of synchronous Motor

If there were no load applied the rotor speed will be equal to the stator (synchronous speed), but the moment load is applied the rotor angle slips back a number of degrees w.r.t the rotating field of the stator.

The equivalent circuit of the one phase of the Synchronous Motor is[4],

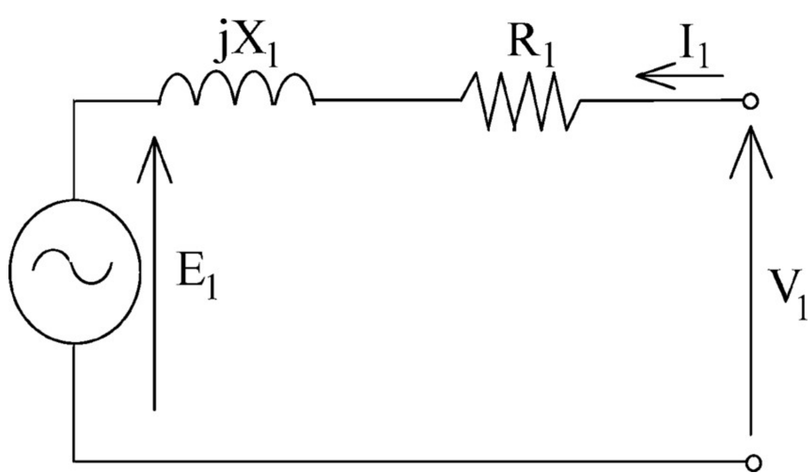

Figure 2 equivalent circuit of a one phase of the synchronous motor

When the rotor field starts rotating at synchronous speed, electrical and magnetic fields in the counter direction of the rotor is induced in the stator windings.

The synchronous speed of the stator depends on:

- The supply frequency (F).
- The number of poles on the stator winding (P).

Synchronous Speed is given by $$N_S = \frac{120\ F}{P}\ r.p.m \qquad (1)$$

The direction of rotation of rotation of a synchronous motor is reversed by interchanging any two of the three lines feeding the stator.[2]

The induced torque resulting from the stator field and rotor field can be calculated as:

Induced Torque $$\tau_{ind} = kB_R\ X\ B_S \qquad (2)$$

And it's also known that, $$\tau_{ind} = kB_R\ X\ B_{net} \qquad (3)$$

$$\tau_{ind} = kB_R\ B_{net} \sin \delta \qquad (4)$$

Where δ is the angle between the rotor magnetic field and the net magnetic field.

The torque developed in the synchronous motor is directly proportional to the applied voltage, and since the motor is a constant speed motor the torque-speed characteristics is parallel to the torque axis as shown in figure 2.[3]

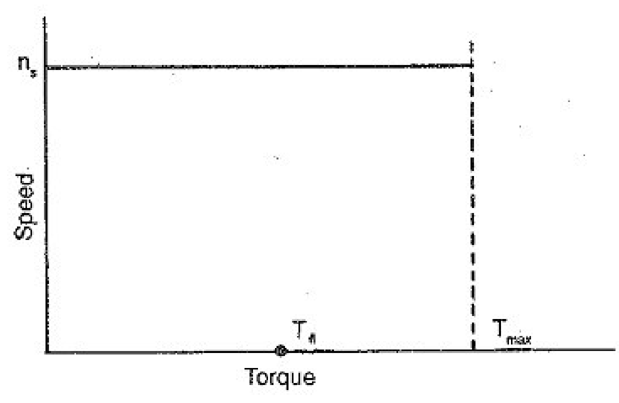

Figure 3 Torque - Speed Characteristics

The maximum torque that the motor can supply called the Pull-out Torque, and its about 2 to 3 times the full load (rated) torque, and it occurs when δ = 90°

Clearly, increasing the field current (B_R) increases the pull-out torque, and when the torque exceeds the Pull-out torque, the rotor is no longer locked to the stator and it slip behind the stator, which makes the stator magnetic field laps repeatedly and the direction of the induced voltage on the rotor keeps reversing, which causes torque surges and vibrations, and causes us loss in synchronization which we call Slipping Poles Phenomenon.

To calculate the efficiency in the Synchronous Motor, the output power and input power should be calculated or measured,

Input Power	$P_{in} = \sqrt{3}\, V_L\, I_L \cos\psi$	(5)
Output Power	$P_{out} = \tau_{ind}\, \omega$	(6)
Efficiency	$\eta_{eff} = \frac{P_{out}}{P_{in}}\, x\, 100\%$	(7)

Slip Ring Motor

The slip Ring induction motor or (asynchronous motor) doesn't operate at the synchronous speed of the rotor.

According to Faraday's Law, when the stator is connected the 3-phase supply, it produces magnetic flux, and the rotor windings get induced and generated a current, and this current leads to develop a torque which makes the rotor rotate.

In order to make the induction motor produce torque, there should be at least some difference between stator speed and rotor speed, and this difference is called the slip

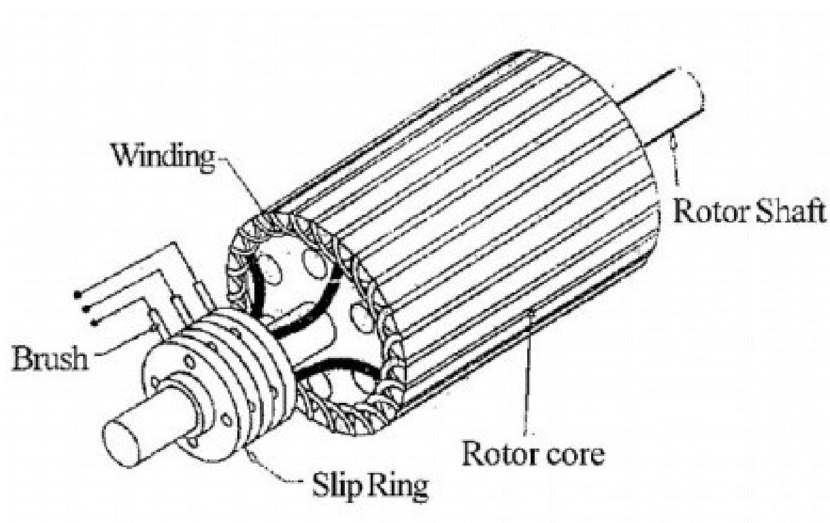

Figure 4 Slip Ring Induction Motor

And since the stator windings induce voltage in the rotor windings in the same way the transformer's primary winding induce voltage in the secondary windings, so the induction motor (slip-ring motor) also called (rotating transformer) the only difference between this motor and transformer is that the secondary part of the transformer is fixed while the rotor is free to move and that's why it's rotating transformer.[5]

Now if a resistor was connected on the rotor, it will have an inverse relation with the speed of the motor[6],

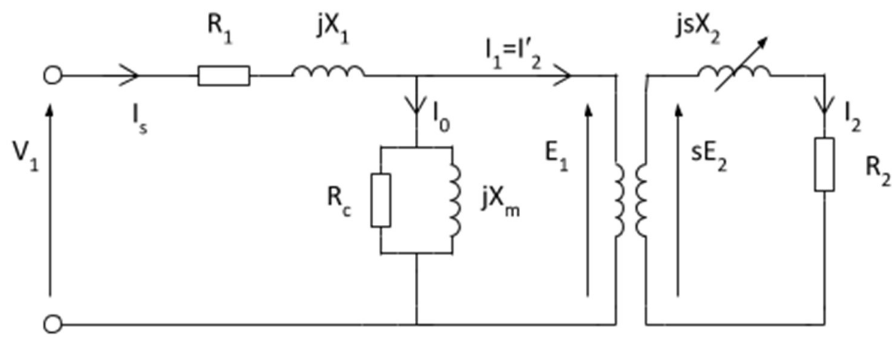

Figure 5 Equivalent circuit of the slip ring motor with rotor circuit

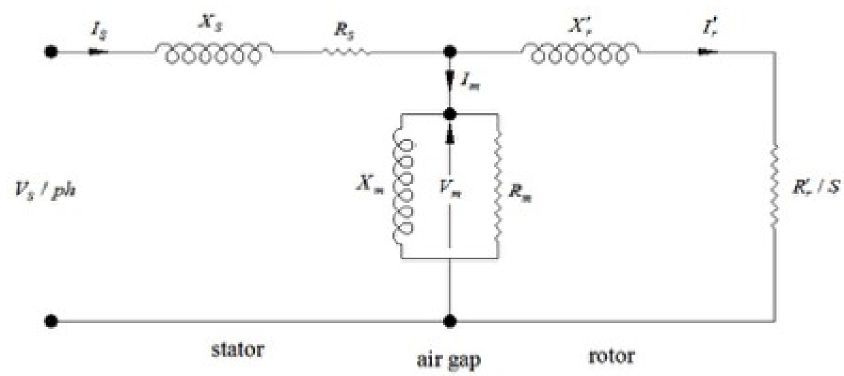

Figure 6 Final equivalent circuit of the slip ring motor

Assuming that $X_m >> X_S$ and $X_M + X_S >> R_S$ then,

$$R_{TH} = R_1 \left(\frac{X_M}{X_M + X_S}\right)^2 \quad (8)$$

$$X_{TH} \approx X_S \quad (9)$$

$$V_{TH} = \frac{X_M}{X_M + X_S} V_1 \quad (10)$$

So, the induced torque will be,

$$\tau = \frac{3|V_{TH}^2|\frac{R_r}{S}}{\omega_{sync}} \quad (11)$$

$$\tau_{ind} = \frac{3|V_{TH}^2|\frac{R_r}{S}}{\omega_{sync}\left[\left(R_{TH} + \frac{R_S}{S}\right)^2 + (X_{TH} + X_r)^2\right]} \quad (12)$$

And after solving the slip at the maximum torque,

$$S_{max} = \frac{3|V_{TH}^2|}{2\omega_{sync}\left[R_{TH} + \sqrt{\left(R_{TH} + \frac{R_S}{S}\right)^2 + (X_{TH} + X_r)^2}\right]} \tag{13}$$

The maximum torque is,

$$\tau_{ind} = \frac{3|V_{TH}^2|}{\omega_{sync}\left[\left(R_{TH} + \frac{R_S}{S}\right)^2 + (X_{TH} + X_r)^2\right]} \tag{14}$$

As noticed from equation 14, the maximum torque is proportional to V_{TH}^2 and inversely proportional to the stator impedance and rotor reactance, also its independent of the rotor resistance.

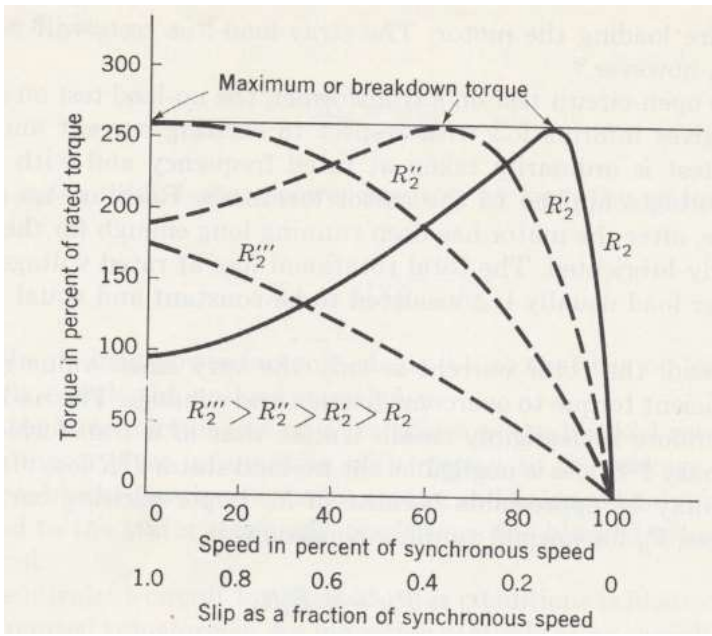

Figure 7 Effect of increasing the rotor resistance at torque and speed

From the figure it can be noticed that the starting torque increases with the increase of the resistance, up to a certain value then it starts decreasing again as it can be seen in case of $R_2''' > R_2''$. [7]

Procedure, Data and calculations

Synchronous Motor

A. Basic Circuit

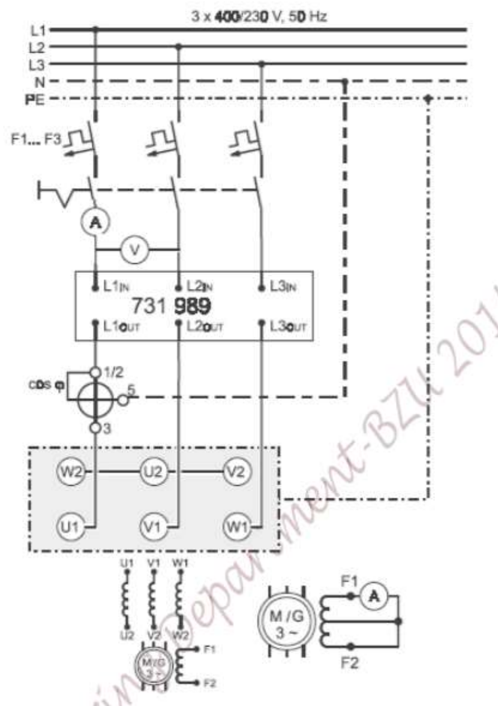

Figure 8 Connection of the synchronous motor used to study its behavior

The circuit in figure 4 was connected, after turning on the power circuit breaker, and directly the value of the current induced in the rotor winding was read, beside the direction and the speed of rotation,

- Startup current = 2.8 A
- Steady-State Current = 0.65 A
- Speed = 1487 r.p.m
- Direction = counter clock wise

Then the power circuit breaker was turned off, and the direction of rotation was reversed by interchanging two of the three phases supplying the stator windings, and the reversed direction and speed were noticed,

- Speed = 1489 r.p.m
- Direction = Clock Wise

The Direction of rotation was turned back to case 1 where,

- Speed = 1487 r.p.m
- Direction = counter clock wise

As noticed the speed was less than synchronous speed and that disagrees with the theoretical part of the synchronous motor, since it's known that the synchronous motor operates at the synchronous speed or doesn't operate at all, but practically its not possible to operate at the exact synchronous speed.

B. Determining Efficiency and Recording Characteristics for SM

A. Efficiency Calculations

The rated values of the machine were taken and recorded in the table down below,

Nominal Voltage V_N when connected in star:	400V
Nominal Voltage V_N when connected in delta:	230V
Nominal Current I_N when connected in star:	0.83A
Nominal Current I_N when connected in delta:	1.44A
Nominal Power Factor, Cos(θ_N) :	1
Nominal Power P_N :	0.27kW
Nominal excitation voltage V_{EN}:	20V
Nominal excitation current I_{EN}:	4A
Nominal speed n_N:	1500

Table 2 Nominal Data for SM machine

Since we have the data above, the Nominal Torque τ_N can be calculated,

$$P_N = \tau_N \ \omega_N$$

$$\tau_N = \frac{P_N}{\omega_N}$$

$$\tau_N = 1.72 \text{ Nm}$$

The input Power can be calculated by

$$P_{in} = \sqrt{3}\ V_L\ I_L \cos\psi$$

$$P_{in} = \sqrt{3} \times 400 \times 0.83 \times 1$$

$$P_{in} = 575.04 \text{ watt}$$

The theoretical efficiency,

$$\eta_{eff} = \frac{P_{out}}{P_{in}}\ x\ 100\%$$

$$\eta_{eff} = \frac{0.27k}{575.04}\ x\ 100\%$$

$$\eta_{eff} = 46.95\%$$

B. Load Characteristics

To test the behavior of the SM, the DC power supply was used to give the value of the Nominal Current I_N = 4A,

And the power circuit breaker was turned on, and the measurement were taken for various values of load torque and recorded in the table down below,

T/TN	0	0.2	0.4	0.6	0.8	1
T	0	0.344	0.688	1.032	1.376	1.72
N	1499	1498	1499	1499	1499	1499
I	0.62	0.15	0.2	0.28	0.36	0.45
COS (ϑ)	1	0.91	0.92	0.935	0.98	0.995
n/Nn	0.999333	0.998667	0.999333	0.999333	0.999333	0.999333
I/IN	0.155	0.0375	0.05	0.07	0.09	0.1125
P1	429.5486	94.56997	127.4789	181.3804	244.427	310.2103
P1/PN	1.590921	0.350259	0.472144	0.671779	0.905285	1.148927
P2	0	53.96335	107.9987	161.9981	215.9975	269.9969
P2/PN	0	0.199864	0.399995	0.599993	0.799991	0.999988
eff	0	0.570618	0.847189	0.89314	0.883689	0.870367

Table 3 Load Characteristic while the excitation current is constant

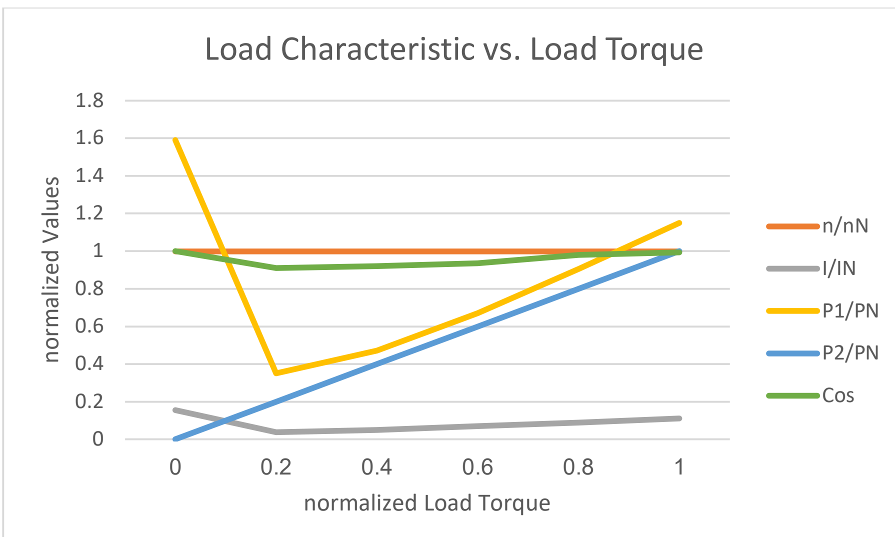

Figure 9 Load Characteristic versus the normalized Load Torque

Where the calculation when T = 0.344 Nm,

Normalized Speed $$\frac{n}{n_N} = \frac{1498}{1500} = 0.9986$$ (8)

Normalized Current $$\frac{I}{I_N} = \frac{0.15}{4} = 0.0375$$ (9)

Input Power $$P_1 = \sqrt{3}\ V_L\ I_L \cos\psi$$ (10)

$$= \sqrt{3} * 400 * 0.15 * 0.91$$

$$= 94.56\ W$$

Output Power $$P_2 = \tau\,\omega = 0.344 * \frac{2\pi}{60} * 1489 = 53.63$$ (11)

Efficiency

$$\eta_{eff} = \frac{P_{out}}{P_{in}} \, x \, 100\% \quad (12)$$

$$= \frac{53.63}{94.56} \, x \, 100\% = 56.7\%$$

It can be noticed from the plot above, that the speed stayed constant while the torque is increasing, while the normalized input and output power increased almost linearly, and this result make sense,

since the output power = $\tau_{ind} \, \omega_N$, so the P_2 is proportional with the torque τ, also current and torque are proportional to each other, and the power factor is almost constant so, the input power increase with the increasing of the current since,

$$P_{in} = \sqrt{3} \, V_L \, I_L \cos \psi$$

C. V Curves and Phase-shift Operation

In this part, Load torque was fixed to a certain value, and the behavior of the stator current was studied on different values of excitation current.

First: Torque was fixed to a value where,

$$\frac{T}{T_N} = 0.25$$

So, T = 0.25 * 1.72 = 0.43Nm

Table 4 Behavior of stator current when torque = 0.43Nm

IE/IEN	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
IE	4	3.6	3.2	2.8	2.4	2	1.6	1.2	0.8	0.4	0
I	0.15	0.14	0.15	0.18	0.215	0.25	0.31	0.38	0.45	0.56	0.61
I/IN	0.0375	0.035	0.0375	0.045	0.0537	0.062	0.077	0.095	0.11	0.14	0.152

Figure 10 I/IN vs. IE/IEN

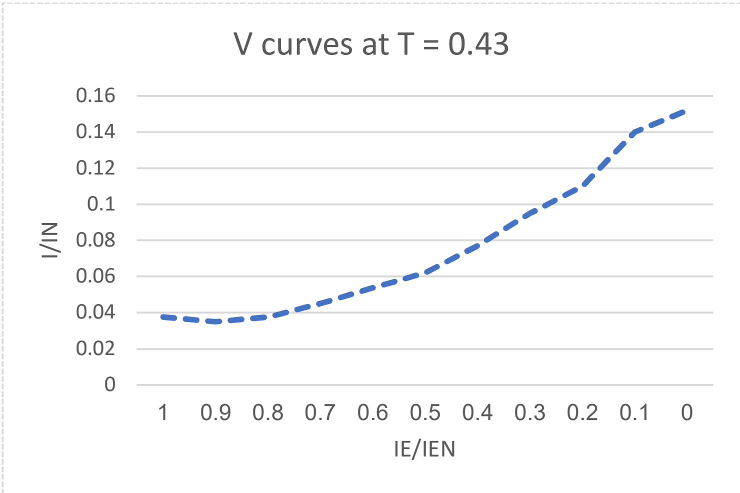

Figure 11 Normalized stator current vs. Normalized excitation current when torque = 0.43Nm

Second: Torque was fixed to a value where,

$$\frac{T}{T_N} = 0.75$$

So, T = 0.75 * 1.72 = 1.29Nm

Table5 Behavior of stator current when torque = 1.29Nm

IE/IEN	**1**	**0.9**	**0.8**	**0.7**	**0.6**
IE	4	3.6	3.2	2.8	2.4
I	0.34	0.34	0.34	0.35	0.39
I/IN	0.085	0.085	0.085	0.0875	0.0975

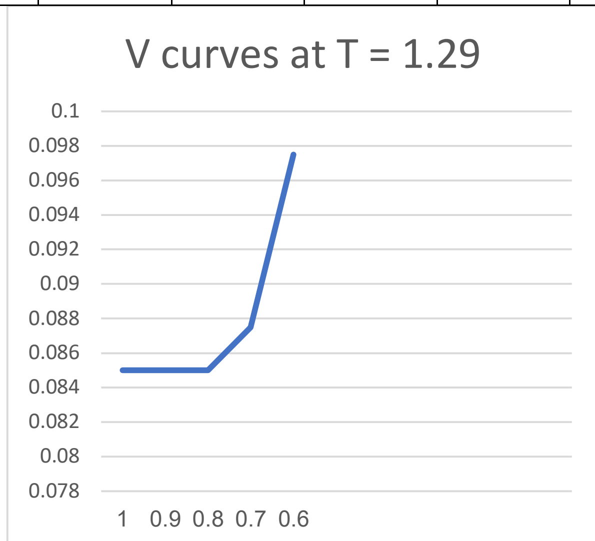

Figure 12 Normalized stator current vs. Normalized excitation current when torque = 1.29Nm

As shown in the data in table 4 and 5, at the unity power factor the current would be at its minimum value, also at the lower values of the excitation current due to the slipping poles phenomenon which is a sudden change in the load in the mains.

Slip Ring Motor

Transformer Operation

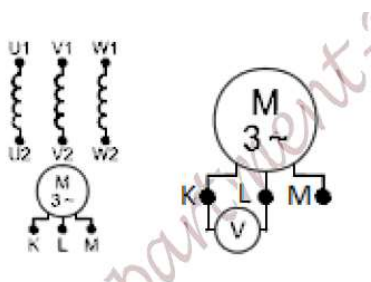

Figure 13 Rotor connection as a transformer in slip ring motor

The rotor was connected as shown in the figure above, and the voltage was measured and found to be,

V = 110V, and this decreasing of the voltage is due to that the slip-ring motor works as a step-down transformer, that's main job is decreasing the voltage.

Now, since the slip-ring motor is an induction motor, it doesn't work at a constant speed (synchronous speed), and to understand the speed of this motor, it was measured on a constant speed and was observed how it changes with the change of the starting resistance.

Table 6 Speed at constant load vs starter resistance

After observing the voltmeter reading, the rotor connection was changed to,

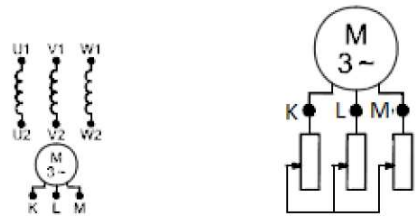

Figure 14 rotor connection with the resistor of the slip ring in the slip ring motor

Table 7 Speed for the slip-ring motor for various values of starter resistance

Position	**6**	**5**	**4**	**3**	**2**	**1**
n/[rpm]	1428	1408	1380	1325	1244	1068

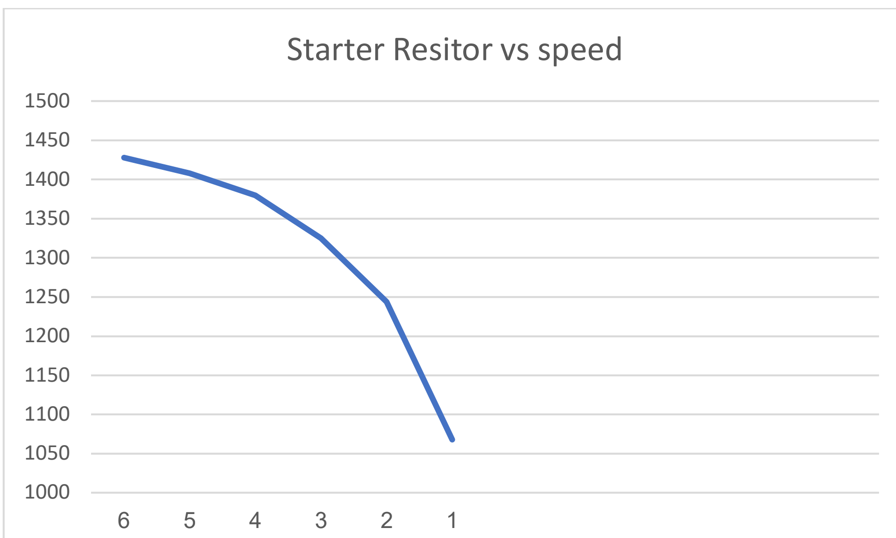

Figure 15 Speed of the motor on constant load vs starter resistor

It can be noticed that with the increasing of the resistor, the speed decreases, since the current decreases with increasing of the resistor, the magnetic field will decrease too, so torque will decrease and by default the speed will decrease too, and that's exactly what happened in table 7.

Note: position 6 is equivalent to no resistance, and position 1 is equivalent to the highest resistance

Computer based Recording of Run-up Characteristics

In this part, CBM 10 Software is needed to plot the behavior of the slip ring motor for various values of starter resistor.

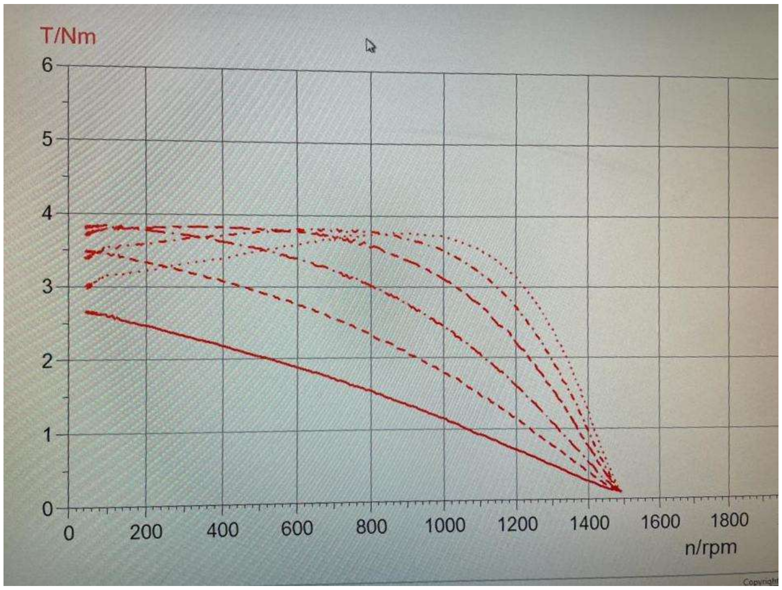

Figure 16 Behavior of the slip ring motor for different values of stater resistor

It can be noticed that the maximum torque doesn't depend on the value of the resistor, but meanwhile it can be seen that the slip (speed) at the maximum value of the torque is proportional to the rotor resistance.

As it seems in the plot, the starting torque keeps increasing up to a certain point at position 2, and then it decreases back at position 1 which it's resistor is greater than position 2's resistor.

Conclusion

To conclude this experiment, it was proven that the synchronous motor works only on the synchronous speed which equal 1500 r.p.m, also that the output and input power of the motor are proportional with the torque while the speed stayed constant as it should be while changing the value of the torque, also it was proven that the induction motor (slip ring motor) doesn't work on synchronous speed, and the starting torque of the induction motor increases with the increase of the rotor resistance up to a value after it, it starts to decrease again, also increasing the rotor resistance will affect the motor slip by increasing and will reduce the motor efficiency and the motor speed, and it will increase the speed regulation.

Theoretical and practical results were reasonable and close to each other, but the plots weren't very accurate, since we didn't take data on a big number of points, but it was close enough to what it was supposed to be.

References

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[7] ENEE2408 Electrical Machines

[8] ENEE3101 Electrical Machines Laboratory

Appendix

... circuit breaker module

Q2: Compare and explain the speed results obtained in **step 13** and in **step 4**

B. Determining Efficiency and Recording Characteristics for SM

a) Efficiency Calculations

1. Using the data printed on the name plate of the machine, fill in Table 5.1

Table 5. 1 Nominal data for the machine under test

Nominal Voltage V_N when connected in star:	400
Nominal Voltage V_N when connected in delta:	230
Nominal Current I_N when connected in star:	0.83
Nominal Current I_N when connected in delta:	1.44
Nominal Power Factor, $Cos(\theta_N)$:	0.7 / 100
Nominal Power P_N :	0.27kW
Nominal excitation voltage V_{EN}:	20
Nominal excitation current I_{EN}:	4
Nominal speed n_N:	~~13~~ 1500

$P_n = W_n T_n$

$T_n = \frac{P_n}{W_n}$

$T_n = 1.72$

2. Using the data obtained in Table 5.1, Calculate the Nominal torque T_N
3. Open the CBM software from Start>>all programs>>CBM10>>MOMO, then go to Measurement>>Settings, set the operational mode to **Torque control** mode
4. Excite the machine with I_{EN} (the nominal excitation current from Table 5.1)
5. Press the ON button of the power circuit breaker module
6. Press the ...

$\frac{T}{T_N} = \frac{Actual}{base} \times base$ $I_N = 4A$

base = T_n

Table 5. 2 Measurement for Load Characteristic Recording with constant excitation current

	T/T_N	0.0	0.1	0.2	0.3	0.4	0.5	0.6
	T/[Nm]	T_NX0.0	0.172	0.344		0688		1.032
Measure	n/[rpm]	1499	[illegible]	1498		1499		1499
	I/[A]	0.62		0.15		0.2		0.28
	Cos (θ)	01		0.91		0.92		0.935
	Lag/lead			Lead		Lead		Lead
calculate	n/n_N							
	I/I_N							
	P_1/[W]							
	P_1/P_N							
	P_2/[W]							
	P_2/P_N							
	η							
	T/T_N	0.7	0.8	0.9	1.0	1.1	1.2	1.3
	T/[Nm]		1.376		1.72		2.064	
Measure	n/[rpm]		1499					
	I/[A]		0.36		0.45			
	Cos (θ)		0.98		0.995			
	Lag/lead		Lead		Lead			
calculate	n/n_s							
	I/I_N							
	P_1/[W]							
	P_1/P_N							
	P_2/[W]							
	P_2/P_N							
	η							

Q5. Plot on the same graph the normalized values (n/n_N, I/I_N, P_1/P_N, P_2/P_N and Cos (θ)) on the Y axis versus normalized Load Torque (T/T_N) on the X axis, explain the behavior of the motor based on your plots?

8. Repeat steps 7 for (T/T_N 0.25, 0.5, 0.75 and 1) this time fill in Tables 5.4, 5.5,5.6 and 5.7 respectively. Make sure that you take the readings that are above the nominal excitation current value quickly. And for low excitation current values, <u>make sure that you press the RED button on the machine test system whenever the machine loses synchronism</u>

T = 0.25 × 1.72 = 0.43

Table 5. 4 Measurement for Recording V Curves at T/T_N=0.25

I_E/I_{EN}	1.1	1.0	0.9	0.8	0.7	0.6
I_E/[A]		4	3.6	3.2	2.8	2.4
I/[A]		0.15	0.14	0.15	0.18	0.215
I/I_N		[illegible]	[illegible]	0.06	[illegible]	[illegible]
I_E/I_{EN}	0.5	0.4	0.3	0.2	0.1	0
I_E/[A]	2	1.6	1.2	0.8	0.4	0
I/[A]	0.25	0.31	0.38	0.45	0.56	
I/I_N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

Table 5. 5 Measurement for Recording V Curves at T/T_N=0.50

I_E/I_{EN}	1.1	1.0	0.9	0.8	0.7	0.6
I_E/[A]						
I/[A]						
I/I_N						
I_E/I_{EN}	0.5	0.4				
I_E/[A]						
I/[A]						
I/I_N						

0.75 × = 1.29

Table 5. 6 Measurement for Recording V Curves at T/T_N=0.75

I_E/I_{EN}	1.1	1.0	0.9	0.8	0.7	0.6
I_E/[A]		4	3.6	3.2	2.8	2.4
I/[A]		0.34	0.34	0.35	0.39	0.39
I/I_N		0.07	0.07	[illegible]	[illegible]	[illegible]

Table 5. 7 Measurement for Recording V Curves at T/T_N=1

I_E/I_{EN}	1.1	1.0	0.9	0.8	0.7
I_E/[A]					
I/[A]					
I/I_N					

9. Press the RED button of the machine test system to isolate the load torque

6. Set the rotor start up resistor to position 6
7. Press the ON button of the power circuit breaker module
8. Press the RED button of the machine test system
9. Set the load torque to be 1Nm (you should be at the torque control mode)
10. Record the speed of the motor when the rotor start up resistor is at position 6, continue for various values of rotor resistor as shown in Table 5.8

Table 5.8 speed for a constant load at various values of starter resistor (position 6: 0 resistance, position 1: highest resistance

Position	6	5	4	3	2	1
n/[rpm]	1428	1408	1380	1325	1244	1068

11. Press the RED button of the machine test system
12. Press the ON button of the power circuit breaker module

Computer based Recording of Run-up Characteristics