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Investigating the Performance of The 3-Phase Synchronous Machine under several operating conditions

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ABSTRACT
This paper investigates the performance of the synchronous machine under several operating conditions throughout several laboratory experiments. Two methods for synchronizing the synchronous machine with network were introduced and examined followed by studying the load characteristics of the synchronous motor with different field exciter currents. Then, the synchronous machine was used as a synchronous generator at no load to verify the saturation curve between the field current and the EMF and to investigate the relationship between the speed and EMF. Moreover, the synchronous generator was loaded to examine its voltage regulation under purely resistive load as well as investigating the effect on its apparent power while loading. Finally, the results in this paper were generated practically and recorded in the results section of this paper with brief description for each milestone, and then they analyzed in detail in the discussion section.
***KEYWORDS**: Synchronous machine, alternator synchronization, synchronous motor loading, saturation curve, synchronous generator loading*

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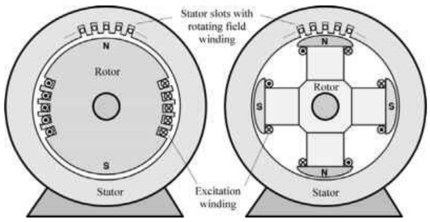
I. INTRODUCTION

The aim for this paper is to synchronize the synchronous machine to a power supply/network using two methods; the synchronizing lamps and the Synchroscope. In addition, to investigate the load characteristics of the synchronous motor under different dc field excitation currents. Furthermore, to obtain the no load characteristics of the synchronous generator for the excitation voltage versus both the excitation current and the speed of the rotor. Finally, to determine the loading characteristics of the synchronous generator.

1.1 Three-phase synchronous machine

As any electrical machine, synchronous machine can be used as a synchronous motor or a synchronous generator depending on application it needs. They are, especially when used as a generator, forming the main source of all the electrical network that we are consumed in our daily life. The stator of the synchronous machine is exactly the same as that in the induction machine. However, the rotor of the machine is exactly the same as in its counterpart of squirrel cage of induction machine except that it is added with a dc field winding that is wound around the squirrel cage coil. Fig.1 illustrates the construction of synchronous machine with two types of rotor: (a) salient rotor used for low speed (b) and cylindrical rotor used for high speed [1]



(a) (b)

Fig.1 Construction of the 3-phase Synchronous machine: (a) salient rotor (b) Cylindrical rotor.
Adapted from 'https://www.freeenergyplanet.biz/'

1.2 Synchronous machine: motor mode operation

When running as a motor, the machine should run first as an induction machine. Therefore, the same sequence of operation as that of the squirrel cage induction machine. When the machine reaches to a speed near the synchronous speed, then with the help of a starter switch, the excitation dc current must be fed into the field winding around the rotor at right moment so to guarantee a smooth operation. In this manner, the rotor of the machine will be locked with synchronous speed of the machine. Thus, this is where the name of a synchronous machine is coming from, because the rotor speed is equal to the synchronous speed. Therefore, the slip of the synchronous machine is equal to zero, and consequently the voltage across the rotor will be zero too [1].

1.2.1 Synchronous Motor equivalent circuit

The synchronous motor can be represented by an equivalent circuit 1φ circuit as shown in Fig.2. Since all the phases are balance, it is easy to deal with a 1φ circuit where 1φ phase source feeding a synchronous reactance Xs and a resistance R (not shown, usually relatively small value) , and a back electromotive force (emf shown as V_O) [1].

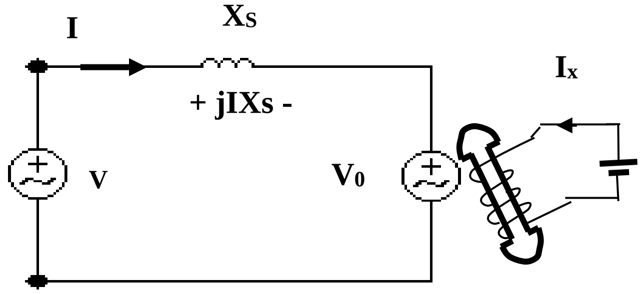


Fig.2 1φ synchronous motor equivalent circuit [1]

1.2.2 Torque and excitation level in synchronous motor

Since the machine also affected by the field of excitation according to the following equation:

$T = k\, \phi\, I_a$ (1)

Hence, by increasing excitation field current I_X in the rotor circuit, the flux ϕ will rise and the pull-out torque of the machine will be relatively higher [5].

1.2.3 DC excitation and reactive power Q in synchronous motor

As the dc excitation in rotor is altered, the value and direction of the reactive power will be changed accordingly. Hence, the synchronous motor can be placed in the electrical network at no load / with a load to improve the power factor of the system. Thus, it will act as a variable inductive reactance or a variable capacitive reactance by varying the dc excitation level in the rotor as shown in Fig.3 [1].

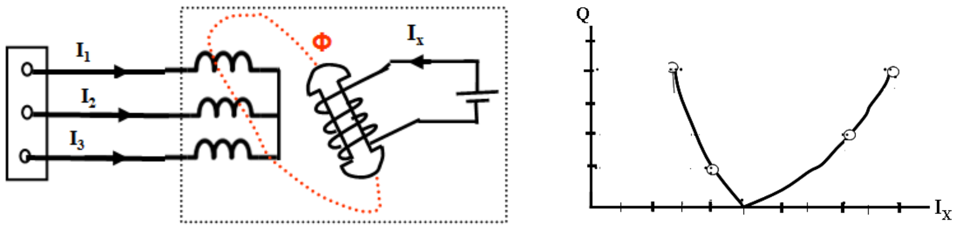


Fig.3 Variation of the I_X and the effect on the reactive power [1],[2]

1.3 Synchronous machine: generator mode operation

In order for the synchronous machine to run as a synchronous generator, a prime mover such as a dc/ac motor or a turbine must be coupled to its shaft and a dc current must be fed to its field winding circuit in the rotor. Thus, three voltages will be induced across the three windings where they are equal in magnitude and displaced 120° from each other [1], [2].

1.3.1 Synchronous generator equivalent circuit

As with the case of synchronous motor, the equivalent circuit is almost the same except that the power supply will be replaced by an electrical load and the direction of the current will be reversed as shown in Fig.4. In this case, when generator is loaded, the internal generated voltage V_O will lead the load voltage V by an angle

δ when the generator under excited and when I leads V, and over excited when I lags V as shown in Fig.5. Thus, the following equation for the power applies here:

$$P = T\,\omega \qquad (2)$$

by being the input mechanical power [1].

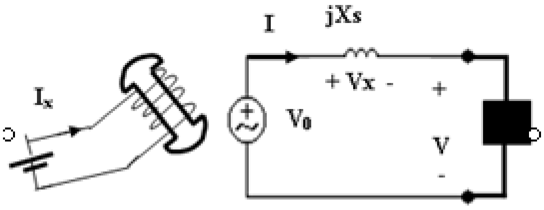


Fig.4 1φ equivalent circuit of a Synchronous generator [1]

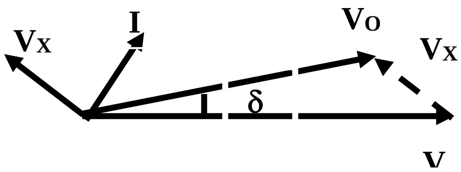


Fig.5(a) Under excited synchronous generator with leading power actor [1]

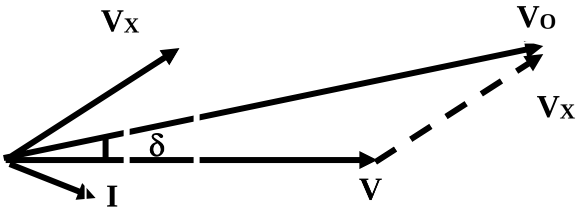


Fig.5(b) over excited synchronous generator with lagging power factor power factor [1]

1.3.2 No load saturation curve for synchronous generator

As introduced in section 1.3, if the synchronous generator runs at no load, the voltage across its windings will be induced when the rotor of the machined rotated by an external source such a turbine and its field winding is fed with the necessary dc excitation current. If the speed is fixed, the voltage of the armature in the machine running at no load (which is the internal generator voltage V_O) will be increased only with the increase of the dc excitation current. Fig.6 shows the relationship between the excitation current I_X and the internal generated voltage V_O. Note how they start to increase proportional to each other until the core of the machine saturated with magnetic flux ϕ which lead less increase of the voltage with large increase of the dc current.

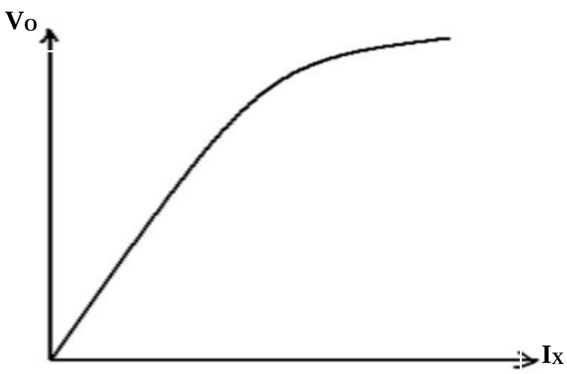


Fig.6 Saturation curve: Exciting current I_X vs. internal generated voltage V_O [1]

II. METHODOLOGY AND RESULTS

The upcoming experiments were performed using the equipment manufactured from German company called Lucas-Nulle. The specifications of the synchronous machine can be found in table 7 in appendix 1.

2.1 Synchronous machine synchronization

To accomplish the synchronization process, the generator that needs to be synchronized must proceed into certain procedures. Two methods, each with different device, are usually used to synchronize the synchronous generator in the final stage, and they are:

(i) Synchronizing using synchronizing lamps

(ii) Synchronizing using synchroscope

2.1.1 Milestone 1: synchronization using lamps

The synchronizing lamps were connected between the supply (network) and the synchronous machine as shown in Fig.7.

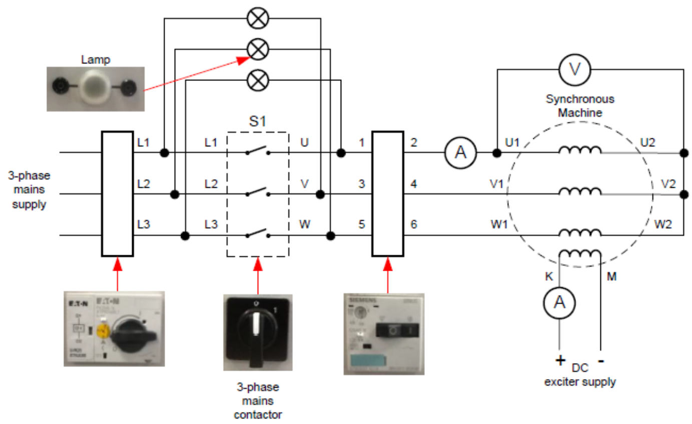


Fig.7 synchronizing using synchronizing lamps [7].

The process of synchronization was accomplished by following practical procedures while the 3-phase main contactor was open, the 3-phase supply was switched on and machine was in speed mode control:

(a) The dc exciter unit was switched on and altered to 1 A dc to energize the stator windings and to make the EMF of the synchronous machine equal to phase voltage of the supply.

(b) The speed of the machine was adjusted by adjusting the control knob of the load machine (prime mover) until all three lamps were illuminating cyclically. As the speed adjusted further and further, the cycling rate of illumination slowed down which means the rotor speed is near the synchronous speed of the network. By adjusting the speed slightly, all the lamps are fully illuminating which means the EMF of the synchronous machine is in phase with the phase voltage of the power supply.

(c) When (a) and (b) were met, the 3-phase contactor switch was closed, and the 3-phase synchronous machine was locked or synchronized to the network and the synchronous speed was measured to be 1500 rpm.

2.1.2 Milestone 2: synchronization using the synchroscope

This method is easy to use where it shows both the relative speed and the phase sequence of the incoming generator. The circuit wiring diagram for this part of the experiment was done according to Fig.8(a) and Fig.(b).

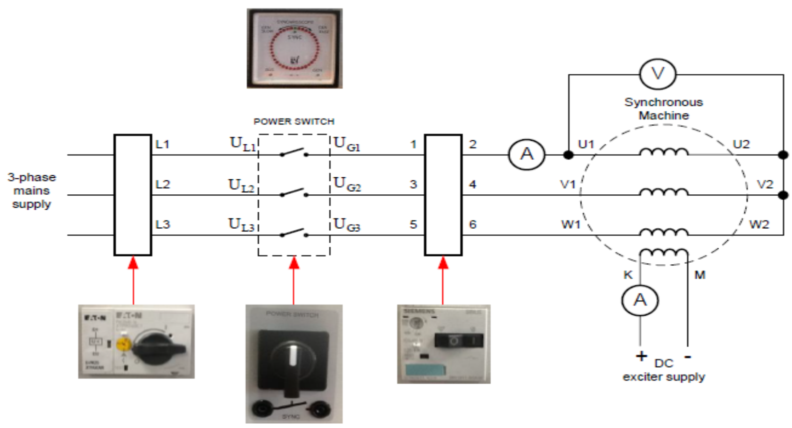


Fig.8(a) synchronizing using synchroscope. [7]

Fig.8(b) The synchroscope. Adapted from bing.com

The process of synchronization was accomplished by following practical procedures while the power switch was open, and the machine was in speed mode control:
(a) The dc exciter unit was switched on and altered to 1 A dc to energize the stator windings and to make the EMF of the synchronous machine equal to phase voltage of the supply. Then, the main power supply was switched on.
(b) The speed of the machine was adjusted by the control knob of the load machine (prime mover) where the frequency indicator was showing a 50 Hz of frequency, which is one of the main conditions of synchronization.
(c) By adjusting the speed further and further, the red LEDS slowed down and reached to a standstill and the green LEDs marked "SYNC" was illuminating. At this moment, the power switch was closed and the machine again as in milestone 1 synchronized to the main power supply (network). The synchronous speed was measured to be 1500 rpm.

2.2 Milestone 3: Load Characterizing-Motoring

In this part of the experiment, the synchronous machine was used as a synchronous motor and its load characteristics with different excitation currents have been tested. After synchronizing the synchronous motor with the power supply, the motor was mechanically loaded with different values of (positive) torques. Then, for different excitation currents; namely: 0.75 A, 1.5 A and 3 A, the speed, stator current and the specified loading torque were all recorded in table 1, table 2 and 3 with respect of the three mentioned excitation currents.
Fig.9 and Fig.10 show the plotting for the toque versus the speed, and the torque versus the current, respectively.

Table 1 Synchronous motor Load characteristics- with 0.75A exciter current.

Exciter current (A)	Stator current (A)	Speed (RPM)	Torque (Nm)
0.75	0.42	1500	0
0.75	0.43	1500	0.1
0.75	0.44	1500	0.2
0.75	0.46	1500	0.3
0.75	0.48	1500	0.4
0.75	0.52	1500	0.5

Table 2 Synchronous motor Load characteristics with 1.5A exciter current.

Exciter current (A)	Stator current (A)	Speed (RPM)	Torque (Nm)
1.5	0.29	1500	0
1.5	0.3	1500	0.1
1.5	0.31	1500	0.2
1.5	0.32	1500	0.3
1.5	0.33	1500	0.4
1.5	0.34	1500	0.5

Table 3 Synchronous motor Load characteristics with 3 A exciter current.

Exciter current (A)	Stator current (A)	Speed (RPM)	Torque (Nm)
3	0.11	1500	0
3	0.13	1500	0.1
3	0.14	1500	0.2
3	0.15	1500	0.3
3	0.18	1500	0.4
3	0.19	1500	0.5

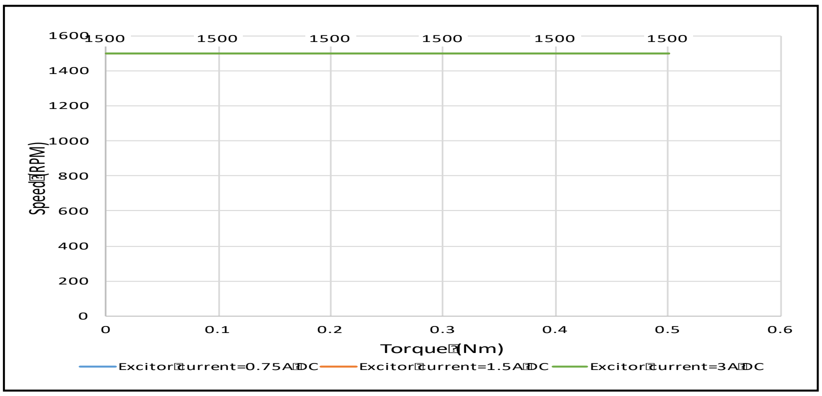


Fig.9 Loading torque Vs Speed

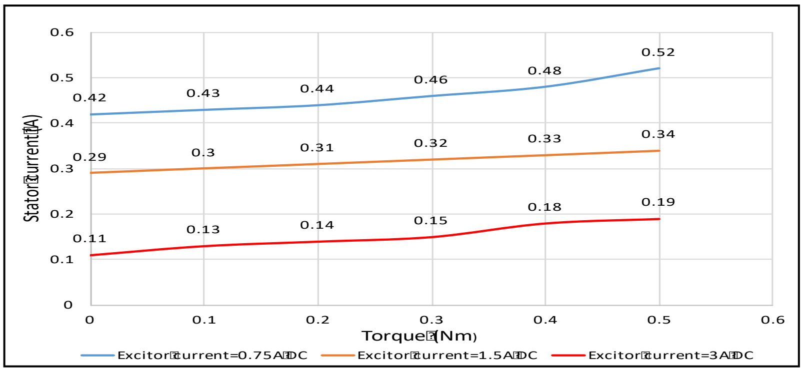


Fig.10 Loading torque Vs. stator current

2.3 Milestone 4: Open-Circuit Characteristic- Generating

In this part of the experiment, the synchronous machine was used as a synchronous generator running at no load by using the load machine as servo motor (prime mover). The following procedures were taken to perform the experiment:

(a) The speed of the rotor was fixed at 1500 rpm (50 Hz of frequency).
(b) The excitation current was adjusted from 0 to 4 A with an increment of 0.5 A, and for every value of current, the open circuit voltage (EMF) was generated and both were recorded in table 4. A plot of the tabulated data is shown in Fig.11.

Table 4 :DC current Vs EMF

DC Current (A)	Emf (V)
0	5.5
0.5	135
1	240
1.5	302
2	340
2.5	360
3	380
3.5	390
4	405

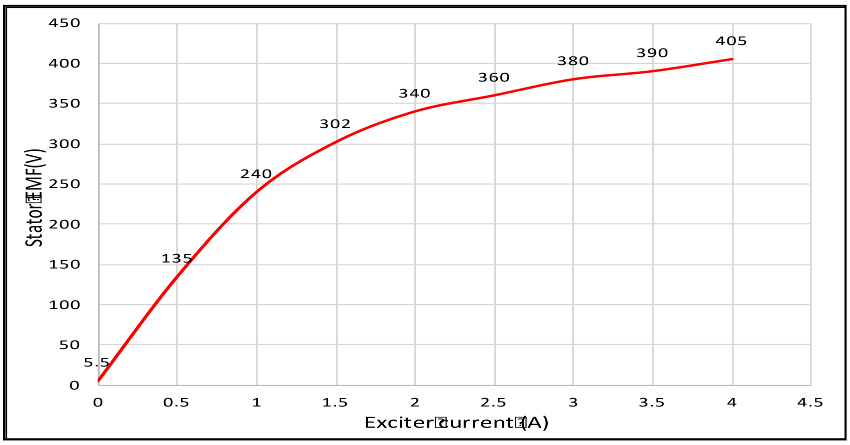


Fig.11 excitation current Vs Emf

2.4 Milestone 5: EMF – Speed Characteristic –Generating

In this part of the experiment, the synchronous machine was used as a synchronous generator running at no load by using the load machine as servo motor (prime mover). The following procedures were taken to perform the experiment:

(a) The excitation current was fixed to 3 A by the control knob of the exciter unit.

(b) The speed of the rotor was adjusted from 500 rpm to 1500 rpm by an increment of 250 rpm, and for every value of speed, the open circuit voltage (EMF) was generated and both were recorded in table 5. A plot of the tabulated data is shown in Fig.12.

Table5Load- characteristic-generating

Speed(rpm)	Stator (voltage
500	130
750	192
1000	255.7
1250	318
1500	375

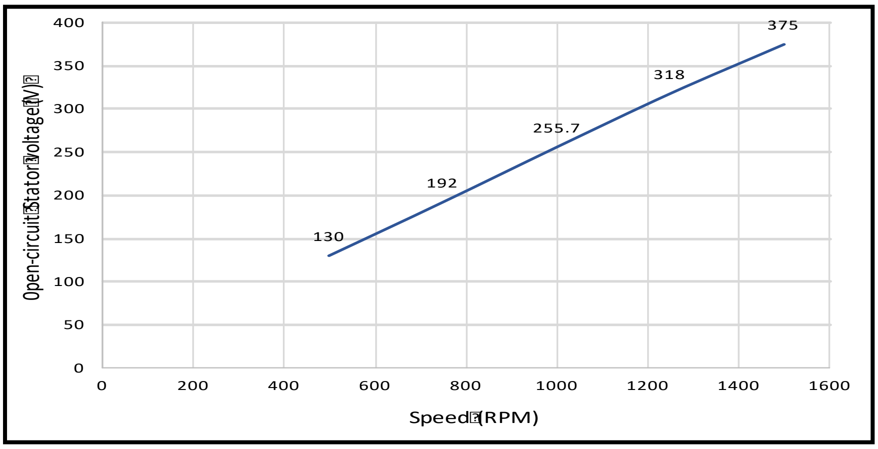


Fig.12 Speed Vs EMF

2.5 Milestone 6: Load characteristics –Generating

In this part of the experiment, the synchronous machine was used as a synchronous generator by using the load machine as servo motor (prime mover). The generator was loaded with a purely resistive load. The following procedures were taken to perform the experiment:
(a) The load machine was set to “speed control mode".
(b) The excitation current was adjusted to 4 A dc. Then generator was loaded with a variable purely resistive load. The resistor is fixed with 1000 Ω, so every time the total required resistance = 1000 + variable resistance.
(c) The speed of the rotor was fixed to 1500 rpm (50 Hz of frequency).
(d) For the required resistance as shown in table 6, the stator current, phase voltage and the apparent power were all recorded. Then, the tabulated data for the stator current vs. the stator voltage and the stator current vs. the apparent power were all plotted as shown in Fig.13 and Fig.14

Table 6 Load characteristics- generating with 4 A exciter current.

Resistive load	Current (A)	Voltage (v)	Apparent power (VA)
2000	0.21	233	45
1500	0.24	228	57
1300	0.29	225	61
1200	0.3	220	70
1100	0.33	215	71

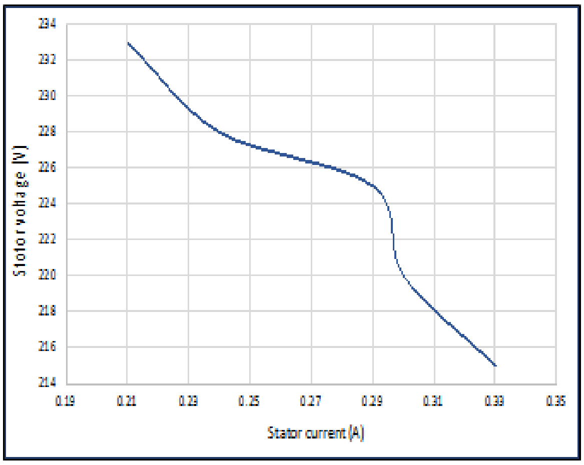


Fig.13 Stator current Vs phase voltage

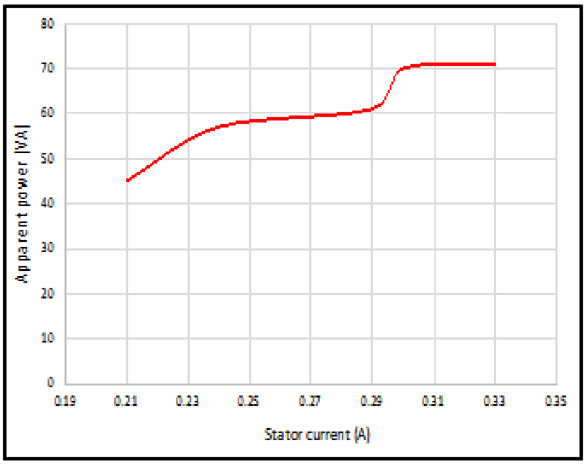


Fig.14 Stator current Vs apparent power

III. DISCUSSION

3.1 Synchronous machine synchronization

In real life the electrical loads are changing through the day and the year. In order to meet the changing demands of electrical power, some generators need to be in service with other working group of generators to cover the shortage of the electrical power in the network and some others need to be disconnected from the service. To accomplish the synchronization process, each EMF of the generator that need to be synchronized must be the same as those voltages in the power supply (or the network) in terms of magnitude, phase and frequency. Two methods, each with different device, are usually used to synchronize the synchronous generator in the final stage, and they are:
(i) Synchronizing using synchronizing lamps
(ii) Synchronizing using synchroscope [7].

3.1.1 Milestone 1: synchronization using lamps

- In this part of experiment the synchronizing lamps were used. In order to meet the requirements for synchronization, the dc excitation current was adjusted to 1 A to give the required EMF for each phase (which is approximately 237 V phase voltage).
- Then, the speed was adjusted by the servo motor (prime mover) in order to match the frequency of the network. Since the synchronous machine is 4-pole machine, then the synchronous speed can be calculated as in the following equation:

$$Ns = 120\frac{f}{p} \qquad (3)$$

$$Ns = 120\frac{(50)}{4} = 1500\, rpm$$

Thus, this is why the speed was adjusted to 1500 rpm to give 50 Hz of frequency.
-The tricky part was to match the phase angle of voltage of the synchronous machine to the phase angle of the voltage of the power supply. While the lights were flickering cyclically, we knew that phase sequence for the generator and the network in the same sequence (i.e.: the two rotors rotating in the same directions). Otherwise, if they were flickering alternately, then we have to either to change any two phases coming from the power supply or any two phases feeding the stator windings. The cycling rate of illumination was the key point to identify the phase matching. When the rate of illumination was slowing down, then we knew that the rotor speed is near the synchronous speed of the network. And when adjusting the speed slightly, all the lamps were fully illuminating which means the EMF of the synchronous machine is in phase with the phase voltage of the power supply [1].

3.1.2 Milestone 2: synchronization using the synchroscope

The synchroscope is widely used in power station during the synchronizing process since it is easy to use where it shows both the relative speed and the phase sequence of the incoming generator which all can be seen into its panel in terms of the frequency indicator and the SYNC LEDs. In order to meet the synchronization condition (Amplitude, voltage, phase and frequency), the frequency indicator was automatically showing a 50 Hz of frequency and the synchronization LEDs must all to be with red color while the SYNC led must show green color. The synchroscope method was done smoothly and easily with accurate results. The rotor speed was 1500 rpm as an indication of 50 Hz of frequency [5].

3.2 Milestone 3: Load Characterizing-Motoring

- In this part of the experiment, the synchronous machine was used as a synchronous motor and its load characteristics with different excitation currents have been tested. After synchronizing the synchronous motor with the power supply, the motor was mechanically loaded with different value of (positive) torque.
- By increasing the rotor excitation current, the torque of the synchronous motor was increased since the magnetic flux in the rotor was increased according to equation 1 ($T= k \phi Ia$) .Hence, the largest pull out torque of the machine was obtained for the biggest excitation current. Also, by altering the flux, the EMF in rotor was affected [1].
- In addition, if the voltage of the power supply is fixed, then by adjusting the field current, the reactive power will be affected and consequently the power factor of the motor. Hence, the synchronous motor can be used as a variable capacitor or as a variable inductor by adjusting the field excitation to improve the overall power factor of the system. Naturally, the armature current will be affected as shown in Fig.15 which represents the V-curve for the field excitation current versus the armature current. From the figure we can conclude:

(a) If the excitation current is minimum, then the motor will appear as a lagging inductive load to the network. Thus, consuming reactive power Q with lagging armature current. (under excited motor)

(b) If the dc excitation is increased further such that Q=0, then the synchronous motor will appear to the network as a purely resistive load with unity power factor and the armature current with the minimum value (fully excited motor).

(c) Finally, if the I_{dc} increased beyond the value found in (b) motor will appear to the network as a

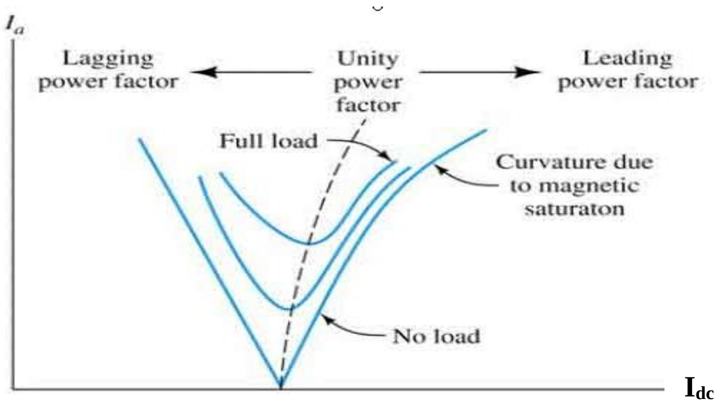


Fig.15 Variation of the I_{dc} and the effect on the armature current I_a. Adapted fromhttps://www.bing.com".

capacitive load. Thus, delivering reactive power Q to the system with leading armature current (over excited motor) [1].
- For fixed supply voltage, adjusting the field current will not affect the active power or the speed of the motor (since P is only affected by altering the mechanical loading and losses in the machine), it only affects the reactive power and the armature current as explained before.
- For a fixed supply voltage, when the excitation current was increased (hence increasing the flux ϕ), the Emf was increased too according to the following equation:

$EMF = 4.44\, f\, N\, \phi_{max}$(4) [1]

and the flux ϕ was rising by increasing the current I_f according to the flowing equation:

$F_m = N\, I = \frac{\phi}{S}$ (5) [6]

and for lagging power factor, when the exciting current was decreasing (EMF decreasing with fixed V_T) , the stator current was increasing according the following equation for the stator circuit :

$V_T = EMF + JX_S I$ (6) [6]

- When the mechanical loading was increasing, the armature current was increasing too since the motor building up more torque according to equation 1 (T= k ϕ I_a) .

- And by adding more torque, the power was increasing too, since the armature current increasing with a fixed voltage for the power supply according to the following equation:

$P = 3\, I_\phi V_\phi\, cos\, \phi$ (7) [3]

3.3 Milestone 4: Open-Circuit Characteristic- Generating

The synchronous machine was used as a synchronous generator running at no load by using the load machine as servo motor (prime mover) while fixing the speed to 1500 rpm. By increasing the field current (hence increasing the flux ϕ), the open circuit of the generator (EMF) was increasing too. This was explained in details in section 3.2 by eq.(4) and (5). From Fig.2, I_X and EMF both increasing in proportional to each otheruntil the core of the machine saturated with magnetic flux ϕ which leads less increase of the voltage with large increase of the dc current.

3.4 Milestone 5: EMF – Speed Characteristic –Generating

The synchronous machine was used as a synchronous generator running at no load by using the load machine as servo motor (prime mover) while fixing the excitation current to 3A dc (thus fixing ϕ). By increasing the speedω, the EMF was rising in proportional to the speed according to the following equation:

EMF = k ϕ ω (8) [5]

3.5 Milestone 6: Load characteristics –Generating

- In this part of the experiment, the synchronous machine was used as a synchronous generator by using the load machine as servo motor (prime mover). The generator was loaded with a purely resistive electrical load. In general, when adding more resistive load in parallel, the equivalent resistance will be less. Therefore, in this experiment when the resistive load was decreasing, the armature current was increasing (load current = armature current) according to Ohm's Law ($I = \frac{V}{R}$), and the output voltage was decreasing as shown in Fig.13. Therefore, with resistive load, the voltage regulation will be poor. The voltage regulation can be found by the following formula:

$$VR\% = \frac{[V_{NL} - V_{FL}]}{V_{NL}} * 100\% \qquad (9) \qquad [5]$$

In addition, the voltage regulation for purely inductive load (L) is very poor, which means that an inductive load (RL) has more poor voltage regulation than a purely inductive load (R). Therefore, for some machines that appears as RL loads in the network such as induction motors, they make large voltage drop in the network. To solve this issue, capacitors loads are usually placed in the network line to compensate the voltage drop and to improve the power factor of the network since adding the capacitor to a generator raises its output voltage [1],[4].

- In Fig.14, when the load current I_a was rising, the apparent power S was increasing too. This is because the increase in current for each value of load resistor is more than that increase in the output voltage according to the following equation:

$$S = \sqrt{3} I_L V_{L-L} \qquad (10) \qquad [3]$$

IV.CONCLUSION

This paper was accomplished to examine the performance of the synchronous machine under several operating conditions. Two methods were utilized in synchronizing the synchronous machine with power supply (network), namely: by using the synchronizing lamps and by using the synchroscope. Both methods were successful in locking the synchronous machine to the network, but the synchroscope approach was easy to be implemented. In addition, the motor load characteristics were investigated with different field excitation currents which led to significant effects on the power factor, motor torque, EMF and the armature current. Furthermore, the saturation curve between the field current and internal generated voltage was verified when the machine was used as a synchronous generator running at no load with fixed speed. Then, the same machine was used to generate a proportional relationship between the speed and EMF while fixing the excitation current. Finally, the synchronous generator was loaded with purely restive load which led to a poor voltage regulation and a rise in the apparent power value.

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VI. Appendix

6.1 Appendix 1 (Machines specifications)

Table 7 : Specification of synchronous machine

specification	Values
Rated power	0.2Kw
Rated voltage	400/230 V, 50Hz
Rated current	0.87/1.5 A
power factor	0.7
Rated speed	1420/1500 rad/sec

Exciter voltage	107V ac / 20V dc
Exciter current	1.7A ac / 4A dc

6.2 Appendix 2

Terms in equations

Eq.(1):
T= Torque of the motor (N.m)
k= constant
ϕ = Excitation field (N.m)
I_a = Armature current (A)

Eq(2) :
P = Input Mechanical Power (w)
T = Driving torque (N.m)
ω = Rotational speed (rad/sec)

Eq.(3) :
N_S = Synchronous speed (rpm)
f = Input frequency (Hz)
p = number of poles in the stator

Eq.(4) :
EMF = induced voltage (V)
f= frequency of the rotor (Hz)
N= number of turn for the winding per phase
ϕ_{max}= the peak value of the magnetic field (Wb)
4.44 = a constant

Eq.(5) :
Fm = magnetic force (A.t)
N= no. of turn
I = current (A)
ϕ=flux (wb)
S= Reluctance (wb/A.turn)

Eq.(6) :
V_T = Terminal voltage (V)
EMF= Induced voltage in the stator winding(V)
X_S = Synchronous reactance (Ω)
I = Stator current (A)

Eq(7) :
P = 3-phase input active power (w)
V_ϕ= phase voltage (V)
I_ϕ = phase current (A) ,
cosϕ = power factor

Eq.(8) :
EMF = Induced voltage (V)
k= constant
ϕ = Excitation field (Wb)
ω = speed (rad/sec),

Eq.(9) :
VR% = voltage regulation
VNL = no load voltage(V), VFL = full load voltage(V)

Eq.(10) :
S= apparent power (VA), I_L= line current (A)
V_{L-L}=line voltage (V)

6.3 Appendix 3

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C Hani Y.Alfahed, et.al. "Investigating the Performance of The3-Phase Synchronous Machine under several operating conditions" *The International Journal of Engineering and Science (IJES)*, 9(01) (2020): 01-14.