Theory and Performance of Series Connected Synchronous Motor

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Abstract: Series Connected Synchronous Motor (SCSM) is an induction motor with stator and rotor windings connected in series. This motor runs synchronously at double nominal speed when runs as normal induction motor (IM). This paper presents theoretical and experimental investigation for steady state performance based on a phasor diagram as derived from relation between voltages, currents and fluxes of the machine.

Keywords: Slip ring induction motor, parametric machine, synchronous motor

LIST OF SYMBOLS

f	frequency of the applied supply voltage, Hz
F_R , F_S , F_t	rotor, stator and resultant MMFs respectively
I_μ	magnetisation current, A
I_a	armature current, A
K	effective rotor to stator turns ratio
l_s , l_r	stator and rotor leakage inductance respectively, H
N_b , N_r	base and operating speeds when the machine runs as I.M and SCSM respectively, rpm
P	number of poles
$P_{o/p}$,$P_{i/p}$,P_f	output and input power and friction losses respectively, W
R_a	armature resistance, Ω
R_s , R_r	stator and rotor resistances respectively, Ω
T	output torque, Nm
V_{AS} , V_{AR}	stator and rotor phase voltage respectively, V
V, E	supply voltage and back emf per phase respectively, V
X_a	armature leakage reactance respectively, Ω
X_m , X_{ms}	magnetising reactance corresponding to N_b and N_r when runs as I.M and SCSM respectively, Ω
θ , ψ , ρ	angles between (F_S & F_t) , (F_R & F_t) and (F_R & F_S) respectively
ϕ	angle between supply current and voltage

I- INTRODUCTION

Operation principle of series connected synchronous machines for generator mode of operation was studied and analysed using d-q model [1], Floquet theory [2] and phasor diagram [3]. Controlling the terminal voltage via excitation capacitor has been presented in [4]using a fixed thyristor controlled reactor. SCSM is basically a three phase slip ring induction machine whose stator and rotor windings are connected in series with sequence of two phases reversed as shown in Fig. 1. With reference to Fig. 2, synchronous mode of operation is possible only when stator and rotor MMFs rotate synchronously opposite to each other at an absolute speed equal to half rotor speed. This machine is capable of operating at higher speeds than conventional induction or synchronous motors fed by same supply frequency. Since rotor and stator windings are connected in series, this machine can operate at higher voltage levels without affecting conductor insulation class. Theory and analysis based on a d-q model has been presented in [5]. In the present paper, the motor mode of operation for series connected machines is studied based on a phasor diagram representation. Theoretical and experimental results are compared and showed reasonable correlation.

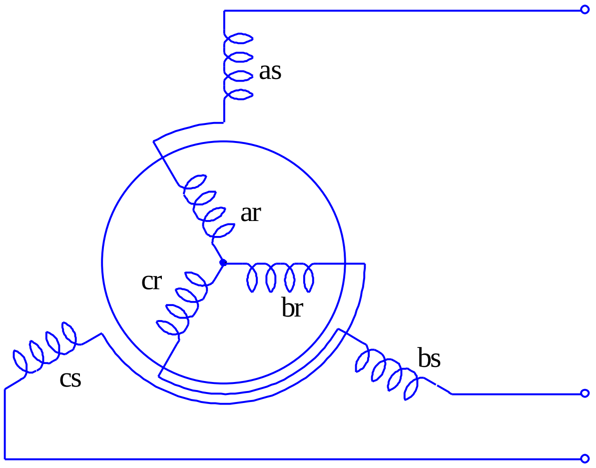


Fig. 1 Schematic diagram of SCSM

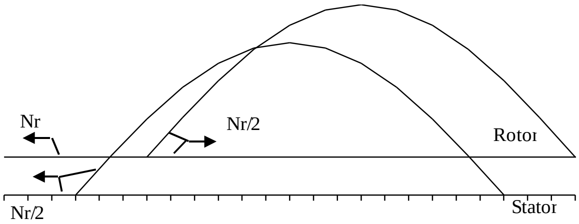


Fig. 2 Stator and rotor MMF's

II- PHASOR DIAGRAM REPRESENTATION

Phasor diagram of SCSM can be determined based on the relation between voltages, currents and fluxes of the machine. As shown in Fig. 3, the machine is symbolically represented as a 2-pole, 3-phase machine. Denoting the angle between stator and rotor MMF axes as ρ, then resultant air gap MMF F_t will lag stator MMF F_S by an angle of θ while leading rotor MMF F_R by an angle of Ψ where:

$$\rho = \psi + \theta \tag{1}$$

Fig.3 shows the rotor position and the MMF's when the armature current is maximum. The instants of maximum rotor and stator phase voltage take place when the resultant MMF coincides with rotor and stator coils. Therefore, the instant of maximum phase current follows that of maximum stator and rotor phase voltages by angles of *(90-θ)* and *(90-Ψ)* respectively as F_t should rotate these angles to coincide with stator and rotor phase coil planes. In phasor notation, stator and rotor phase voltages V_{AS} and V_{AR} respectively can be expressed by:

$$\bar{V}_{AS} = V_{AS}\ e^{j\left(\frac{\pi}{2}-\theta\right)} \tag{2}$$

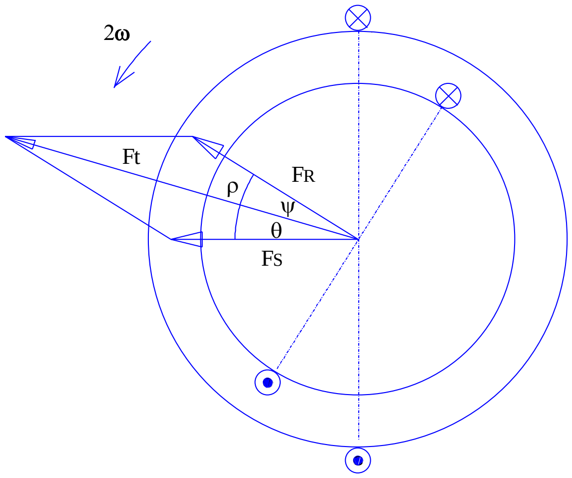


Fig. 3 Symbolic representation of 2-pole 3-phase SCSM

$$\bar{V}_{AR} = V_{AR}\ e^{j\left(\frac{\pi}{2}-\psi\right)} \tag{3}$$

Since same flux cuts both stator and rotor phases at same speed and by assuming an effective turns ratio of K, then:

$$F_R = K F_S \tag{4}$$

Therefore,

$$V_{AR} = K V_{AS} \tag{5}$$

Regarding MMF relationship of Fig. 3, it is seen that:

$$F_R\ \sin(\psi) = F_S\ \sin(\theta) \tag{6}$$

Substituting by (4) into (6) yields:

$$K\ \sin(\psi) = \sin(\theta) \tag{7}$$

Also, total MMF F_t is related to stator MMF F_S and rotor MMF F_R by:

$$F_t = \sqrt{F_R^2 + F_S^2 + 2F_R F_S \cos(\rho)} \tag{8}$$

Subsequently, the magnetisation current I_μ is related to armature current I_a by:

$$I_\mu = I_a\sqrt{1+K^2+2K\cos(\rho)} \tag{9}$$

Conventional no-load test for 3-phase induction machine is carried out at base speed N_b corresponding to nominal motor frequency yielding the evaluation of magnetisation reactance X_m.
Denoting magnetisation reactance of SCSM as X_{ms} where:

$$X_{ms} = \frac{V_{AS}}{I\mu} = \frac{V_{AS}}{I_a\sqrt{1+K^2+2K\cos(\rho)}} \tag{10}$$

Since field rotates at half rotor speed N_r, the corresponding value of X_{ms} is given by:

$$X_{ms} = X_m\ \frac{N_r}{2N_b} \tag{11}$$

Substituting by (10) into (11) and rearranging result in:

$$\frac{V_{AS}}{I_a} = X_m\ \frac{N_r}{2N_b}\sqrt{1+K^2+2K\cos(\rho)} \tag{12}$$

The supply voltage V equals back emf plus voltage drop across resistances and leakage reactances of both rotor and stator.

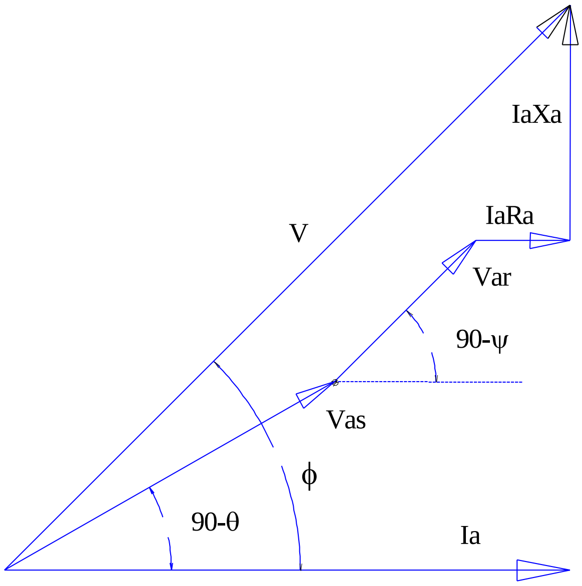


Fig. 4 Phasor diagram of SCSM

Following previous relations, a phasor diagram can be constructed as shown in Fig. 4.
It is seen that:

$$V\cos(\phi) = I_a R_a + V_{AS}\sin(\theta) + V_{AR}\sin(\psi) \qquad (13)$$

$$V\sin(\phi) = I_a X_a + V_{AS}\cos(\theta) + V_{AR}\cos(\psi) \qquad (14)$$

where,

$$R_a = R_s + R_r$$

$$X_a = 2\pi f\left(l_s + l_r\right)$$

$$f = \frac{PN_r}{240}$$

For each value of ψ, the values of the six unknowns θ, ρ, I_a, V_{AS}, V_{AR} and ϕ can be evaluated by solving the six simultaneous equations (1), (5), (7), (12), (13) and (14).

III- TORQUE AND POWER EXPRESSIONS

Saturation and eddy current losses are neglected. The input power $P_{i/p}$ is given by:

$$P_{i/p} = 3VI_a\cos(\phi) \qquad (15)$$

The output power $P_{o/p}$ can be expressed as:

$$P_{o/p} = 3I_a E\cos(\alpha) - P_f \qquad (16)$$

where,

$$\bar{E} = E\, e^{j\alpha} = \bar{V}_{AS} + \bar{V}_{AR} \qquad (17)$$

The net electromechanical torque T is expressed by:

$$T = \frac{P_{o/p}}{\left(\frac{2\pi N_r}{60}\right)} \qquad (18)$$

IV- EXPERIMENTAL TEST RIG

The experimental set-up is made from a slip ring three phase induction motor whose details are given in Table 1. The parameters as have been obtained by standard tests at 50 Hz are given in Table 2. The induction machine is connected in the SCSM mode as shown in Fig. 1 and coupled to a DC dynamometer, which enables torque measurement. The speed is measured by an ac tachometer. Also phase voltage, current and input power are recorded. Starting methods of SCSM are similar to conventional synchronous motor. In this test, the machine is fed from a conventional synchronous generator to facilitate starting and speed control.

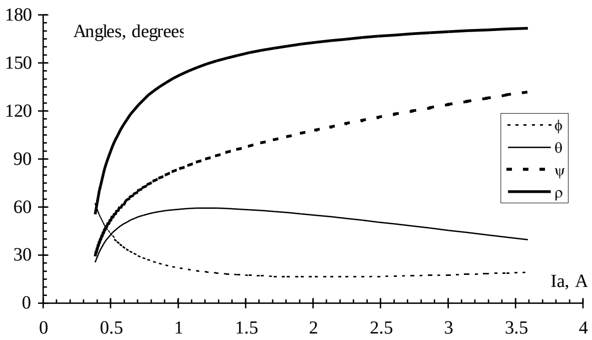
V- RESULTS AND DISCUSSION

Experimental tests have been carried out at a frequency of 25 Hz and a maximum line voltage of 135V as obtained from the supplying synchronous generator at this low frequency. Thus, the running speed of SCSM is 1500 rpm. The parts of Fig. 5 show the relation between motor angles, voltages, torque, power and efficiency versus motor current. The experimental results were limited by motor rated current (3.6A). Besides the supplying synchronous generator pulls out of synchronism after that current. From Fig. 5, it can be concluded that the correlation between experimental and theoretical results shows reasonable matching which proves the validity of the suggested model. It can also be concluded that the input power factor cos(ϕ) is high. This is attributed to the high inductance ratio L_d/L_q as concluded from d-q model [5] (approximately 40). The armature current always lags stator phase voltage while it lags and leads rotor phase voltage. The motor power factor is always lagging like induction motor and unlike conventional synchronous motor whose power factor is lagging or leading. The input power is low compared to rated value. This is because of using low applied voltage which can be increased to about 700 V because of series connection of rotor and stator. Increasing applied voltage results in wider range and enables obtaining more power to weight ratio than conventional induction machine. Because of high speeds this machine would have better cooling. It is expected for unity turns ratio machine that the performance would be better because the stator and rotor voltage will be in phase and therefore the power factor will be improved.

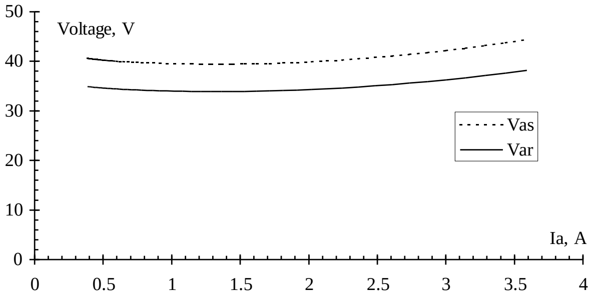
TABLE 1. IM DETAILS
220/380V, 6.3/3.6 A
2.2 kW,
50 Hz,
4 pole
1390 rpm

TABLE 2. IM PARAMETERS

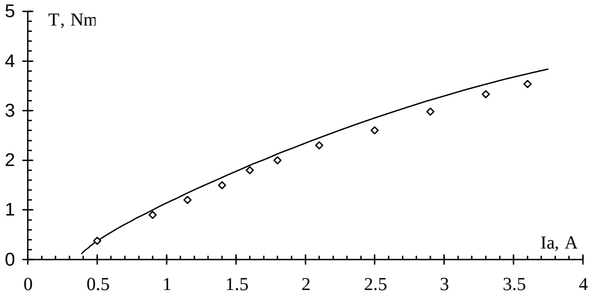
$R_s = 2.08\ \Omega$,
$R_r = 1.96\ \Omega$,
$l_s = 16.81$ mH,
$l_r = 12.48$ mH,
$K = 0.86$ and
$X_m = 104.5\ \Omega$.



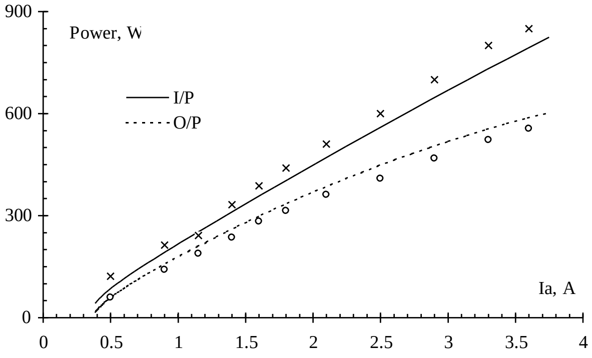
(a)



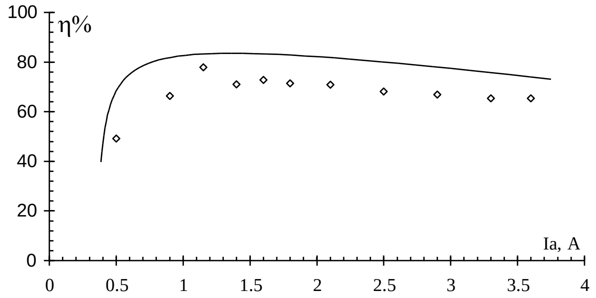
(b)



(c)



(d)



(e)

Fig. 5 Relationship between motor current and (a) motor angles, (b) phase voltages, (c) developed torque, (d) power and (e) efficiency (points = measured & lines = calculated)

VI. CONCLUSION

SCSM runs synchronously at double rated speed when it runs as an induction motor depending on number of motor poles and supply frequency. Like synchronous motors, this motor is not self starting and it starts with the same methods as the conventional synchronous motor. Saturation and eddy current losses were neglected. The steady state performance has been studied based on a deduced phasor diagram. Comparison between experimental and theoretical results showed satisfactory agreement which proves the validity of the suggested phasor diagram. The results can be considered as a useful guide to operate and design three phase SCSM.

VII. REFERENCES

[1] A.S. Mostafa, A.L. Mohamadein and E. M. Rashad, " Analysis of series connected wound-rotor self excited induction generator", IEE Proc. B, Vol. 140, No. 5, Sept. 1993, pp. 329-336.

[2] A.S. Mostafa, A.L. Mohamadein and E. M. Rashad, "Application of Floquet's theory to the analysis on series connected wound rotor self excited synchronous generator", IEEE Trans. on EC, Vol. 8, No. 3, Sept. 1993.

[3] A.L. Mohamadein and E.A. Shehata, "Theory and performance of series connected self excited synchronous generator", IEEE Trans. on EC, Vol. 10, No. 3, Sept. 1995.

[4] M. EL-Shanawany, "Capacitor controlled self excited series connected synchronous generator", Eng. Research Bulletin, Faculty of Engineering, Menoufia University, Vol. 17, Part I, 1994.

[5] E. Rashad, M. Abdel-Karim and Y.G. Dessouky, "Theory and analysis of three phase series connected parametric motors", IEEE Trans. on EC, Vol. 11, No. 4, Dec. 1996.

VII. BIOGRAPHIES

Yasser Gaber Dessouky was born in Alexandria, Egypt, 1969. He got the B.Sc. and M.Sc. in Electrical and Control Engineering from Alexandria University, Egypt in 1991 and 1993 respectively. He obtained the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K. in 1998 Since 1991 he has been employed in the Department of Control and Electrical Engineering of the Arab Academy of Science and Technology, Alexandria, Egypt. His research interest includes modelling and simulation of electric machines, power electronics, machine drives and microprocessor applications.

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