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 it 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, Ω
X_m , X_{ms}	magnetising reactance corresponding to N_b and N_r when it 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, degrees
φ, α	angle between the supply current and both the supply voltage and back emf respectively, degrees

I- INTRODUCTION

The doubly fed induction motor was the subject of quite a lot of theoretical and experimental investigation both as a motor and as a generator [1]-[3]. The operation principle of series connected synchronous machines for generator mode of operation was studied and analysed using a d-q model [4], Floquet theory [5] and phasor diagram [6]. Controlling the terminal voltage via excitation capacitor has been presented in [7]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 the same supply frequency. Theory and analysis based on a d-q model has been presented in [8]. 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 which show reasonable correlation.

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, the resultant air gap MMF F_t will lag behind the stator MMF F_S by an angle of θ while leading the 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 coil planes. 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:

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

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

Since the same flux links both stator and rotor phases at the 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 the MMF relationship of Fig. 3, it is seen that:

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

Substituting (4) into (6) yields:

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

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

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

The magnetisation current I_μ is related to the armature current I_a by:

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

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 the 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 (10) into (11) and rearranging will 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 the back emf plus the voltage drop across resistances and leakage reactances of both rotor and stator. Following previous relations, a phasor diagram can be constructed as shown in Fig. 4. It is seen that:

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

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

where,

$$R_a = R_s + R_r$$

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

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

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:

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

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

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

where,

$$\overline{E} = E\ e^{j\ \alpha} = \overline{V}_{AS} + \overline{V}_{AR} \tag{17}$$

The net electromechanical torque T is expressed by:

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

IV- EXPERIMENTAL TEST RIG

The experimental set-up is made with a slip ring three phase induction motor whose details are given in Table 1. The parameters 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 machine runs at its rated synchronous speed, 1500 rpm. The experimental results were limited by motor rated current (3.6A). Besides the supplying synchronous generator pulls out of synchronism after that current. The parts of Fig. 5 show the relation between motor angles, voltages, torque, power and efficiency versus motor 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 ratio of the direct inductance, L_d to the quadrate inductance L_q as concluded from d-q model [8] (approximately 40). The armature current always lags behind the stator phase voltage while this current lags and leads behind the rotor phase voltage. The motor power factor is always lagging like in an 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 that can be increased to about 700 V. This is because the rotor and stator windings are connected in series and therefore this machine can be designed to operate at higher voltage levels. Increasing applied voltage results in a wider range and enables obtaining more power to weight ratio than a conventional induction machine. SCSM is suitable for high speed applications. Because of high speeds this machine would have better cooling. If the same fan on the end of the rotor is used when the machine runs as both SCSM and IM fed from the same supply frequency and voltage, the windage losses are greater for SCSM which results in lower efficiency. However, the windage losses are considered constant and small over this range of operation. 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 Ω,
R_r = 1.96 Ω,
l_s = 16.81 mH,
l_r = 12.48 mH,
K = 0.86 and
X_m = 104.5 Ω.

VI. CONCLUSION

SCSM runs synchronously at double rated speed when it runs as an induction motor depending on the 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 useful guides for design operation of three phase SCSMs.