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DERIVATION OF THE CIRCUIT PARAMETERS FOR A SLEEVE ROTOR INDUCTION MACHINE

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ABSTRACT
The field analysis using cylindrical coordinates for sleeve rotor induction machine is discussed. The magnetic field equations are carried out applying a simple model. The electric loading of rotor and the air gap flux density are calculated and plotted as a function of the machine speed. The effect of the sleeve material is taken into consideration.
The stator phase induced voltage is determined, and the air gap impedance is obtained in terms of machine design geometry. The individual sleeve rotor resistance, leakage reactance, and stator to rotor mutual reactance expressions are simplified for a minimum calculation effort.

1. INTRODUCTION
The sleeve rotor of a smooth conducting cylinder mounted on an iron core may allow a good starting machine conditions[1]. A simplified cross section of a sleeve rotor induction machine is shown in Fig.1. In addition to the conventional application, the sleeve rotor will lead to more development of future modified machine.

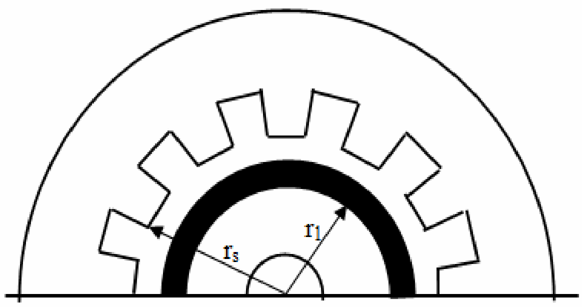

Figure.1, simplified cross section of sleeve rotor machine

Where r_s is the inner stator radius, r_1 is the iron rotor radius. In order to completely describe the machine performance, it is necessary to derive an expression for the air gap impedance [2]. This can be carried out using the two-dimensional field theory in cylindrical coordinates [3,4]. It is possible to obtain the air gap impedance in a single step from the vector potential equation [5].
In addition, this method of analysis enables the effects of machine physical design data to be easily taken into account.

Expressions for the individual equivalent circuit parameters of the sleeve rotor are derived and simplified by introducing some practical considerations [6,7]. These parameters are calculated and tabulated for different values of the sleeve rotor design data.

2. THE FIELD ANALYSIS

2.1 Field Model

The field problem is based on an idealized model of the sleeve rotor induction machine. The stator and rotor iron cores have very high permeability. Also, much effort can be saved by neglecting the current displacement in the rotor sleeve which is extremely weak. Accordingly, the field calculation is based on one-region model shown in Fig.2.

An infinitesimal1y thin sleeve sheet is assumed, to possess a finite surface conductivity:

$$\sigma' = \sigma . t_s \qquad (1)$$

where t_s and σ are the actual values of the rotor sleeve thickness and its conductivity, respectively.

The stator windings are replaced by a current sheet carrying the stator electric loading As. The complex amplitude of the stator electric loading wave for m_s phases is given by:

$$\widehat{A}s = -j\ m_s \frac{2w_s\ k_w}{2\pi\ r_s} \sqrt{2}\ Is \qquad (2)$$

where w_s is the number of stator turns per phase, and K_w is the stator winding factor.

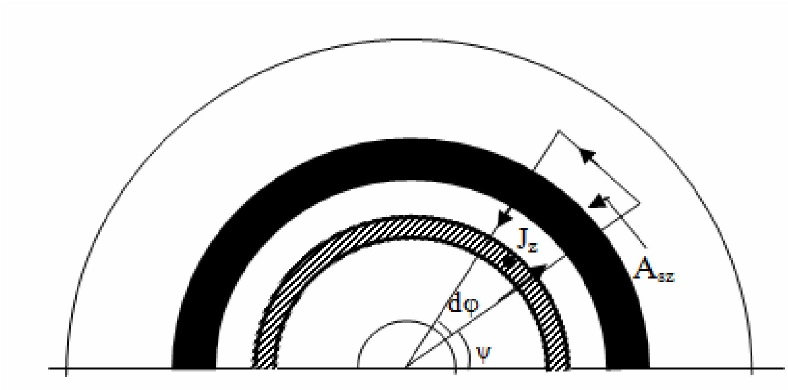

Fig. 2, one region model for a sleeve rotor

2.2 The Solution of the Field Equation

Only axial current is assumed to flow in the model so, the vector potential possess only an axial Z-component

$$V_z(r,\emptyset,t) = \mathrm{Re}\,(V_z(r)e^{j(\omega t - P\varphi)}), \qquad (3)$$

where P is a number of pole pair.

From the magnetic and electric field equations, the differential equation for the complex amplitude of the vector potential V_z is given in the form:

$$r^2 \frac{\partial^2 V_z}{\partial r^2} + r \frac{\partial V_z}{\partial r} - P^2\ V_z = 0. \qquad (4)$$

The solution of this equation is:

$$Vz = C_1 rP + C_2\ r - P, \qquad (5)$$

the unknown integration constants C_1 and C_2 can be determine using the following model boundary conditions:

At both air gap-stator and rotor boundaries, the tangential component of the magnetic field intensity is applied with taking the stator and rotor electric loadings into consideration.

$$-\frac{1}{\mu_0}\frac{\partial V_z}{\partial r}\,|r_s = A_s, \qquad (6a)$$

$$-\frac{1}{\mu_0}\frac{\partial V_z}{\partial r}\,|r_1 = A_r. \qquad (6b)$$

The rotor electric loading A_r can be, at first, expressed in terms of the magnetic vector potential as:

$A_r = -\, j\sigma\,\omega\, sV_z\,|r=r1$, from equation (5)

$$A_r = -\, j\sigma'\omega s\,[\,C_1\, r^{P} + C_2\, r^{-P}\,] \qquad (7)$$

Solution of equations (6 and 7), gives the following results:

$$C_1 = -\,\frac{\mu_0 A_s}{p}\, r_s^{p+1}\, \frac{1+jKS}{r_s^{2P} - r_1^{2P} + jKS\,(r_s^{2P}\, r_1 + r_1^{2p+1})} \qquad (8a)$$

$$C_2 = C_1\, r_s^{2P} + \frac{\mu_0 A_s}{P}\, r_s^{2p+1} \qquad (8b)$$

with $K = w\sigma'\mu_0\, r1 \,/\, P$ (8c)

Substitution of C_1 and C_2 into Eq.(5), determines the vector potential Vz.
Thus, the radial flux density component at the stator surface is

$$B_r|r_s = -\, j\,[C_1\, r_s^{p-1} + C_2\, r_s^{-(p+1)}\,], \qquad (9a)$$

which can be used in determining the induced magnetization voltage. Equation (9a), can be represented in the form

$$Br|r_s = B_0\, \frac{(r_s^{2P} + r_1^{2P}) + jKS\,(r_s^{2P} - r_1^{2P})}{(r_s^{2P} + r_1^{2P}) + jKS\,(r_s^{2P} + r_1^{2P})^2 \,/\, (r_s^{2P} - r_1^{2P})} \qquad (9b)$$

where the no load flux density

$$B_o = j\, \frac{\mu_0 A_s}{P}\, \frac{r_s^{2P} + r_1^{2P}}{r_s^{2P} - r_1^{2P}} \qquad (9C)$$

The sleeve rotor electric loading is obtained from (7) and (8) to be

$$A_r = A_s k\, \frac{r_s^{2P} + r_1^{2P}}{r_s^{2P} - r_1^{2P}}\, s\, \frac{r_s^{2P} + r_1^{2P} + jKS\,(r_s^{2P} - r_1^{2P})}{r_s^{2P} + r_1^{2P} + jks\,[(r_s^{2P} + r_1^{2P})^2 \,/\, (r_s^{2P} - r_1^{2P})]} \qquad (10)$$

The air gap flux density and the rotor electric loading are important quantities for all the design procedure. The normalized flux density and rotor electric loading can be calculated and plotted as function of the machine speed. Fig.3, shows the variation of the amplitudes of radial flux density and the rotor electric loading as functions of the slip for high and low sleeve conductivities.

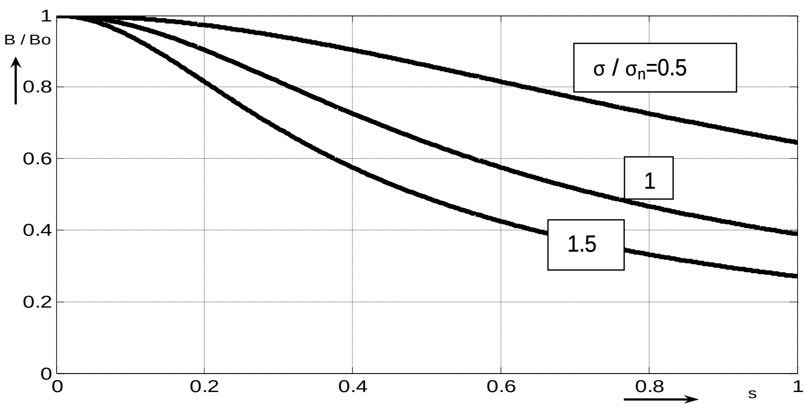

Fig. 3.a variation of B as function of slip

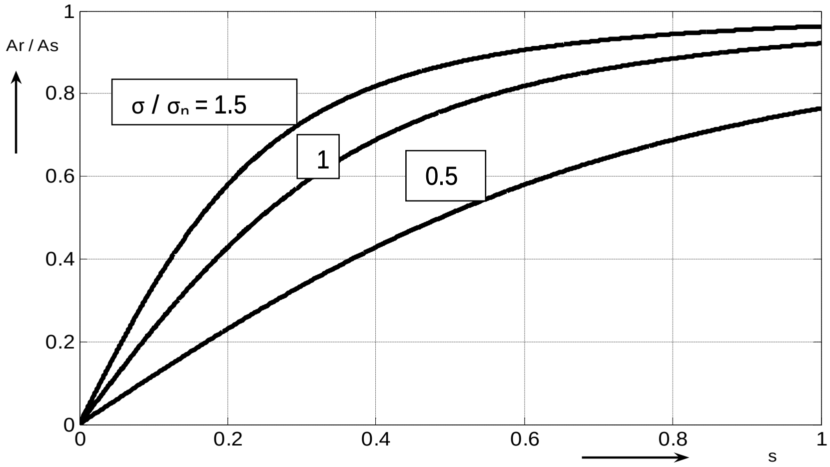

Fig. 3.b variation of Ar as function of slip

At synchronous speed, s = 0.0, no voltage is induced in the sleeve, and there is no rotor current and the magnetic field has its no load value Bo. Thus, the difference between the air gap flux density at load and the no load value is an immediate measure of the intensity of the rotor armature reaction.

The proceeding simple field analysis gives the air gap flux density and the rotor electric loading, now the next step is to determine an equivalent circuit representation for the sleeve rotor.

3. THE AIR GAP IMPEDANCE AND THE SLEEVE PARAMETERS

The main characteristics of the machine can be given if the stator electric loading is determined. In order to calculate the stator current, it is necessary to derive an expression for the air gap impedance Z_g.

The stator magnetization voltage induced by the air gap field is expressed by

$$E_s = j \frac{\omega}{\sqrt{2}} (w_s \ k_s) \ L \ \frac{2\pi r_s}{2p} \cdot \frac{2}{\pi} B_g \ |r_s \qquad (11)$$

substituting from Eq. (8), the stator e.m.f. becomes

$$E_s = j \ \omega \ \mu_o \ m_s L \ (w_s \ k_s)^2 \ \frac{2}{\pi p^2} \ \frac{r_s^{2P} + r_1^{2P} + (js\omega \ \sigma \ \mu_o \ r_{1/p})(r_s^{2P} - r_1^{2P})}{r_s^{2P} - r_1^{2P} + (js\omega \ \sigma \mu_o \ r_{1/p})(r_s^{2P} + r_1^{2P})} . I_s \qquad (12)$$

The air gap impedance is therefore given by

$$Z_g = E_s / I_s \qquad (13a)$$

which may be written as

$$Z_g = ja \ \frac{r_s^{2P} + r_1^{2P} + jk \ s(r_s^{2P} - r_1^{2P})}{r_s^{2P} - r_1^{2P} + jk \ s(r_s^{2P} + r_1^{2P})} \qquad (13b)$$

with $a = \omega \ \mu_o \ m_s \ L \ \frac{2}{\pi p^2} (\ w_s \ k_s \ )^2$ (13c)

Extending both numerator and denominator of Eq. (13b) by $a / K(r_s^{2P} + r_1^{2P})^2$ and arranging the resulting equation, yield the following expression:

$$Z_g = ja \ \frac{(r_s^{2P} + r_1^{2P})}{(r_s^{2P} - r_1^{2P})} \left[\frac{a(r_s^{2P} + r_1^{2P})^2}{4k \ r_s^{2P} \ r_1^{2P}} + js \ \frac{a(r_s^{4P} - r_1^{4P})}{4 \ r_s^{2P} \ r_1^{2P}} \right] /$$
$$\left\{ \frac{a(r_s^{2P} + r_1^{2P})^2}{4k \ r_s^{2P} \ r_1^{2P}} + js \left[\frac{a(r_s^{4P} - r_1^{4P})}{4 \ r_s^{2P} \ r_1^{2P}} + a \ \frac{(r_s^{2P} + r_1^{2P})}{r_s^{2P} - r_1^{2P}} \right] \right\} \qquad (14)$$

The well-known equivalent circuit of Fig.4, is proposed to represent the induced voltage across the magnetizing reactance X_m in parallel with the sleeve rotor impedance.
Referring to Fig.4, the impedance can be written in a form suitable for comparison with Eq (14) as:

$$Z_g = jX_m \frac{R_r' + js\,x_{1r}'}{R_r' + js\,(X_m + x_{1r}')} \tag{15}$$

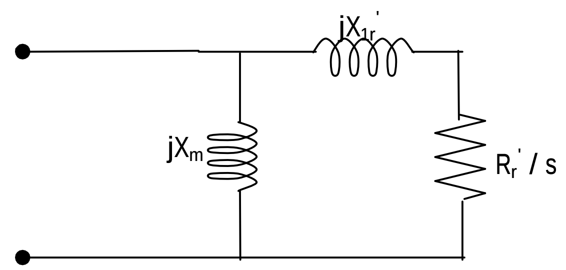

Fig. 4. usual sleeve rotor equivalent circuit

By comparing Eqs. (14) and (15), the individual parameters of the sleeve rotor equivalent circuit are obtained in the forms:

$$X_m = a\,\frac{r_s^{2P} + r_1^{2P}}{r_s^{2P} - r_1^{2P}} \tag{16a}$$

$$x_{1r}' = a\,\frac{r_s^{4P} - r_1^{4P}}{4\,r_s^{2P} r_1^{2P}}\ , \tag{16b}$$

$$R_r' = a\,\frac{(r_s^{2P} + r_1^{2P})^2}{4k\,r_s^{2P}\,r_1^{2P}}\ . \tag{16c}$$

The equivalent circuit parameters are computed for different design data of a sleeve rotor.
Table 1, contains the design data for different machines and the corresponding values of Xm , R_r', and x_{1r}' . The main design data are : r_{sn} = 5 cm, Ln = 10 cm, t_{sn} = 0.5 mm, g_n =0.2 mm, and σ_n = 5 107 S.

Table 1, the design data and the corresponding equivalent circuit parameters.

σ / σ_n	t_s/t_{sn}	g/g_n	r_s/r_{sn}	L/L_n	X_m	R_r'	x_{1r}'
1	1	1	1	1	75	8.7	.06
2/3	1	1	1	1	75	13	.06
1	8/5	1	1	1	52.4	5.5	.086
1	1	5	1	1	87.8	8.7	.051
1	1	1	4/5	1	60	10.6	.051
1	1	1	1	4/5	60	6.9	.048

Since the actual sleeve is replaced in the used model by an infinitesimal1y thin current sheet, there is no skin effect. Then, the individual equivalent circuit parameters are clearly independent on the rotor speed.
quince values. Consequently, the forward and backward current components, which enable the machine performance are determined.

4. CONCLUSIONS

The results of the simplified analysis carried out here, give the principal expressions of the air gap flux density and the sleeve rotor electric loading. The sleeve resistance, leakage reactance, and the stator to rotor mutual reactance equations are simplified and carefully arranged for a minimum calculation effort. This method of analysis enables the effects of changing the design data to be directly taken into consideration.

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