# ON THE SEGMENTED ROTOR RELUCTANCE SYNCHRONOUS MOTOR SALIENCY RATIO CALCULATION

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**Summary** The reluctance synchronous motor performance highly depends on its saliency ratio. Therefore an accurate analytical calculation of the motor's saliency is quite a necessity within the designing procedure. In this paper an analytical method to calculate the main motor inductances and its saliency ratio is applied to a segmented rotor reluctance synchronous motor. The results obtained for two motor variants, compared with the ones obtained via a 2-D FEM computation and via tests, stand by to prove the proposed technique accuracy.

## 1. INTRODUCTION

Converter fed variable reluctance synchronous motor can be an important competitor in the variable speed drives market due to its reduced production costs, good controllability at low speed and a quite high efficiency [1].

The variable reluctance synchronous motor (VRSM), also known as synchronous reluctance motor, is a single salient machine. The VRSM produces torque due to its rotor tendency to move to a position where the flux of the excited winding and its inductance, are maximized. This type of machine does not require field winding or permanent magnets on the rotor. The stator of a VRSM, identical with that of the induction machine, has uniform distributed slots and usually a three-phase distributed single or double layer winding.

The performance (torque, power factor and efficiency) of a VRSM is dependent on the saliency ratio K=$M_d / M_q$, which is the ratio of the d-axis ($M_d$) and q-axis ($M_q$) magnetizing inductances. A large saliency ratio means an important rotor magnetic asymmetry, which can be obtained by adopting a segmental structure, by employing the flux barriers or by using the axially-laminated (ALA) construction [1, 2, 3, 4]. The rotors with multiple flux barriers and axially laminated rotors offer the possibility of achieving high saliency ratios, but have the disadvantages of their quite complicated technology and high costs. In some applications, when the drive cost has a major importance, the simplest structure with a smaller saliency ratio should be adopted. Such a structure, as the segmented rotor is, must be designed very carefully in order to obtain the maximum saliency ratio, therefore the parameters calculation is important.

The goal of this paper is to obtain the motor parameters and especially the saliency ratio by a quite simple analytical technique. The obtained results, for two motors, are compared with the numerical (2D-FEM) and test calculated values.

## 2. PARAMETERS AND SALIENCY RATIO ANALYTICAL CALCULATION

In order to calculate the d- and q- axis inductances of a VRSM machine, a cylindrical rotor machine will be first considered. It has the air gap length equal to the minimal air-gap ($g_1$) of VRSM [5]. The magnetizing inductance of a cylindrical rotor is given by:

$$M_{mc} = 3 \cdot \frac{D_i \cdot L_i \cdot Q_s \cdot \mu_0}{1.4 \cdot g_1 \cdot \pi} \cdot \left( \frac{k_{ws} N_s}{p} \right)^2 \qquad (1)$$

with: $D_i$ – stator interior diameter, $L_i$ – axial length, $Q_s$ – number of stator slots, $N_s$ – number of stator turns, p – number of pole pairs, $k_{ws}$ – stator winding factor .

For a motor with a cylindrical rotor, the air-gap flux density fundamental is:

$$B_1 = \frac{\mu_0 \cdot F}{g'} \qquad (2)$$

where F is the resultant stator mmf and g' is the enlarged equivalent air-gap, considering the stator slots opening, via Carter's factor $k_C$ and core saturation :

$$g' = k_s \cdot k_C \cdot g \qquad (3)$$

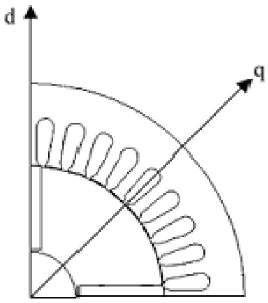
The saturation coefficient $k_s$ can be estimated in the usual designing manner or calculated based on 2D-FEM calculations.

If the stator MMF centered on the d-axis has a co-sinusoidal variation in function of the rotor position angle θ, then the fundamental component of flux density on the d-axis come as [5]:

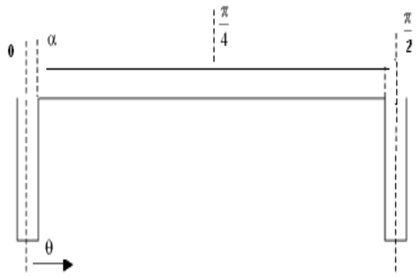
$$B_{ld} = \frac{4}{\pi} \cdot \mu_0 \cdot \int_0^{\frac{\pi}{2}} \frac{F \cdot \cos^2 \theta}{g(\theta)} d\theta \qquad (4)$$

For the MMF centered on the q-axis:

$$B_{lq} = \frac{4}{\pi} \cdot \mu_0 \cdot \int_0^{\frac{\pi}{2}} \frac{F \cdot \sin^2 \theta}{g(\theta)} d\theta \qquad (5)$$




a)




b)

*Fig. 1. VRSM segmented rotor*
*a) configuration, b) simplified scheme*

These relations, in the case of the rotor structure given in Fig.1a, accordingly to the simplified scheme adopted, Fig. 1b became:

$$B_{ld} = \frac{4}{\pi} \cdot \mu_0 \cdot \left[ \int_0^{\alpha} F \cdot \frac{\cos^2\theta}{g_2} d\theta + \int_{\alpha}^{\frac{\pi}{4}} F \cdot \frac{\cos^2\theta}{k_s \cdot g_1} d\theta \right] \quad (6)$$

$$B_{lq} = \frac{4}{\pi} \cdot \mu_0 \cdot \left[ \int_0^{\alpha} F \cdot \frac{\sin^2\theta}{g_2} d\theta + \int_{\alpha}^{\frac{\pi}{4}} F \cdot \frac{\sin^2\theta}{g_1} d\theta \right] \quad (7)$$

where $g_2$ is the maximal air gap equal to 30mm and the angle α is 3.065 deg , Fig. 1b, and, as expected, the saturation is considered only on the d-axis, (6).

The flux density coefficients are:

$$k_d = \frac{B_{ld}}{B_1} \qquad k_q = \frac{B_{lq}}{B_1} \quad (8)$$

which means for this case:

$$k_d = \frac{4 \cdot g_1}{\pi} \left( \int_0^{\alpha} \frac{\cos^2\theta}{g_2} d\theta + \int_{\alpha}^{\frac{\pi}{4}} \frac{\cos^2\theta}{k_s \cdot g_1} d\theta \right) \quad (9)$$

$$k_q = \frac{4 \cdot g_1}{\pi} \left( \int_0^{\alpha} \frac{\sin^2\theta}{g_2} d\theta + \int_{\alpha}^{\frac{\pi}{4}} \frac{\sin^2\theta}{g_1} d\theta \right) \quad (10)$$

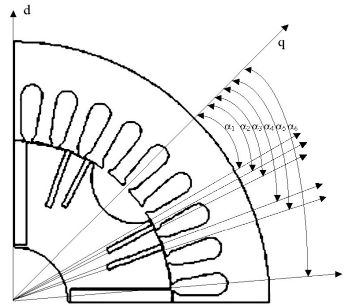
Similar equations were obtained for the rotor with more complicated topology, given in Fig.2 [4].

The longitudinal and transversal magnetizing inductances are:

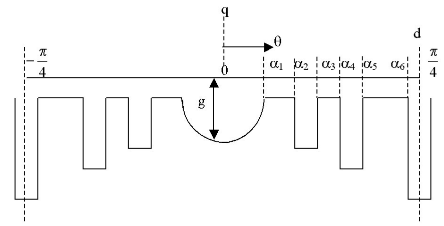
$$M_d = k_d \cdot M_{mc}$$
$$M_q = k_q \cdot M_{mc} \quad (11)$$

The saliency ratio is given as:

$$K = \frac{M_d}{M_q} = \frac{k_d}{k_q} \quad (12)$$




a)




b)

*Fig. 2. VRSM segmented rotor with flux barriers*
*a) configuration, b) simplified scheme*

In fact the saliency ratio is influenced by the stator leakages and the effective value of the ratio is smaller:

$$K^* = \frac{L_d}{L_q} = \frac{M_d + L_{S\sigma}}{M_q + L_{S\sigma}} = \frac{K + K_{\sigma q}}{1 + K_{\sigma q}} \quad (13)$$

where:

$$K_{\sigma q} = \frac{L_{S\sigma}}{M_q} \quad (14)$$

Suppose that $K_{\sigma q} \rightarrow 0$, which is not the case for this size of machines, than $K = K^*$, but since $M_q$ and $L_{S\sigma}$ values are quite comparable it is clear hat $K < K^*$.

For a designer three rules are emerging:

i) Make $M_d$ as large as possible and do not saturate the iron-core.
ii) Make $M_q$ as small as possible.
iii) Obtain the smaller possible value for $L_{S\sigma}$

The stator phase leakage inductance depends on the stator slot shape, on the stator winding and on the end winding topology. The calculations were done considering the usual formulae [5, 6], but with a certain attention on the air-gap leakages due to the very specific rotor configuration and to the higher harmonic content of the air-gap field density.

## 3. 2D-FEM COMPUTATION

A 2-D finite element method (FEM) analysis would offer different accuracy, but it requires longer computer time. Two simplifying assumptions were considered:

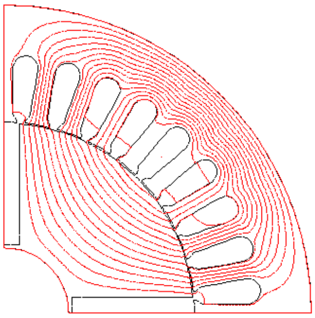
i) The rotor's eddy currents are neglected.
ii) The iron core hysterezis is neglected too

For the determination of main d- and q-axis inductances, the currents were imposed in the stator slots in order to generate a longitudinal, respective a transversal reaction magnetic field. For the VRSM with segmented rotor, Fig. 1, the flux plots obtained through a 2-D FEM analysis are given in Fig. 3 (a, b).

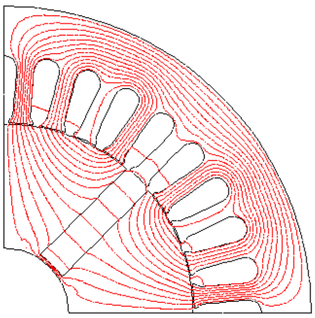
The inductances were obtained using quite a usual and simple method in numerical calculation.

First the air-gap magnetic flux was calculated on both axes, $\Psi_d$, $\Psi_q$, then the magnetizing inductances,

$$M_d = \frac{\Psi_d}{i_d} \qquad M_q = \frac{\Psi_q}{i_q} \tag{15}$$



a)



b)

*Fig. 3. VRSM with segmented rotor flux plots a) on d-axis, b) on q-axis*

## 4. EXPERIMENTAL METHOD

The experimental method involved zero speed operation at a predetermined rotor position [7]. One phase of the machine was fed with a low voltage at the base frequency and the rotor was positioned in an aligned and unaligned position. For these positions of minimal and maximal reluctances a set of voltage, current and power measurements were done.

Based on the measured values the phase impedances and resistances, including the iron core losses equivalent resistances, were computed and the reactance of one phase is obtained for the both axis.

$$X_d = \sqrt{Z_d^{\,2} - R_d^{\,2}} \tag{16}$$

$$X_q = \sqrt{Z_q^{\,2} - R_q^{\,2}} \tag{17}$$

The stator winding leakages were obtained by testing the stator winding without the rotor inside. Respecting the same procedure like at the analytical computation the saliency ratio was obtained (relation 12).

## 5. RESULTS AND CONCLUSIONS

The calculations and tests were carried on two three phase VRSMs with segmented rotor. Their main data are given in Table 1 and the rotor topologies are shown in Figures 1a and 2a. A view of the segmented rotor, the one shown in Figure 1, is given in Figure 4, the stator being identical to one of an induction motor, as are the case and the other mechanical parts. The main motors dimensions are given in Table 2.

*Fig. 4. A view of the segmented rotor of the considered VRSM*

The obtained results obtained for saliency ratio are given, for both machines, in Table 3.

In the paper a technique for analytically calculation of the d- and q-axis VRSM magnetizing inductances and, consequently of the machine saliency ratio is presented. The technique, which is quite at hand and can be easily developed for other rotor structures, is applied on two different rotor topologies inductance and saliency ratio calculation.

In both cases a 2-D FEM calculation was carried on and the corresponding main inductances calculated at rated current. The complex tests were conducted for the same purpose.

*Tab. 1. VRSMs main data*

| | | |
|---|---|---|
| Rated induction base machine output power, kW | 2,2 | 5.5 |
| Phase supply voltage, V | 230 | 230 |
| Rated induction base machine phase current, A | 5.1 | 12.4 |
| Rated speed, rpm | 1425 | 1500 |
| Phase connection | star | star |
| Number of stator slots | 36 | 36 |
| Number pole pairs | 2 | 2 |
| Air-gap length, m | $0.35 \cdot 10^{-3}$ | $3.5 \cdot 10^{-3}$ |

The 2D-FEM computed saliency ratio values are larger than the analytically calculated ones in both cases due to the simplifications made in the analytical calculation. The tests obtained values differences in comparison with the 2D-FEM calculated ones are quite large, but the test methodology has some limits.

As it can be noted, the results are quite close, for both rotor configuration considered, which prove that the analytical developed technique leads to quite accurate results, and that it can be adequately introduced within any design algorithm of such machines.

*Tab. 2. Main dimensions of the tested VRSMs*

| STATOR | | ROTOR | |
|---|---|---|---|
| Exterior diameter | 0.15m/0.2m | Exterior diameter | 92.3mm/ 117mm |
| Inner diameter | 93 mm/ 124mm | Pole number | 4/4 |

*Tab. 3. Saliency ratio coefficients*

| **Model** | $K=M_d/M_q$ | | |
|---|---|---|---|
| | **Analytical** | **2D-FEM** | **Tests** |
| Fig.1 | 3.183 | 3.584 | 3.062 |
| Fig.2 | 3.98 | 4.14 | 4.36 |

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