Physica C 470 (2010) 98–103

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

# Reluctance machines incorporating high temperature superconducting materials on the rotor

A.L. Rodrigues [a], A.J. Pires [a,b,*]

[a] Uninova-CTS, Faculdade de Ciências e Tecnologia/UNL, Lisboa, Portugal
[b] Instituto Politécnico de Setúbal, Setúbal, Portugal

ARTICLE INFO

*Article history:*
Received 14 June 2009
Received in revised form 19 October 2009
Accepted 23 October 2009
Available online 3 November 2009

*Keywords:*
Reluctance machines
Finite element method
High temperature superconducting materials

ABSTRACT

The computer modelling of reluctance machines with rotors containing both iron and high temperature superconducting (HTS) materials, using the finite element method (FEM), is presented in this paper. The modelling permits to obtain the field and stator current distribution from where reluctance torque is evaluated. Different solutions are analyzed and experimental results on a 2 kW reluctance motor using HTS materials on the rotor and cooled by liquid nitrogen, show a significant increase in the torque values, when compared with that of a correspondent conventional machine. Pre-magnetization of these rotors by field cooling is explained and this process gives a mechanical output power undoubtedly better than that of a conventional reluctance machine.



## 1. Introduction

Conventional reluctance motors theory is nowadays very well known [1]. Due to the simple rotor construction, robustness and easy winding commutation by means of power electronic circuits (inverters), reluctance motors have today a large industrial application. The main disadvantage is to exhibit much less output torque than the equivalent salient pole synchronous motor.

During the last two decades many different reluctance rotor configurations have been considered in order to improve output power and efficiency of these type of motors [2–4]. Recently, a number of international research groups (*Department of Engineering Science, Oxford University, UK*; *Cambridge University, UK*; *Moscow State Aviation Institute, Russia*; *Institut fuer Physikalische Hochtechnologie, Jena, Germany*; *Institute de Ciencia de Materials de Barcelona, Bellaterra, Spain*; *CTS-UNINOVA, Caparica, Portugal and also in USA and Japan*), have explored the possibility of using high temperature superconducting (HTS) materials in the construction of hysteresis and reluctance electrical machines using bulk yttrium–barium–copper oxide elements (known as YBCO) placed in the rotor.

The ceramic YBCO is a type-II HTS with a critical temperature $T_c$ of 94 K. This compound is achievable with dimensions of centimetres and when cooled with cheap and readily available liquid nitrogen (77 K), can carry large current densities in the region of $10^4$ A/cm$^2$ [5] without any dissipation to provide high magnetic flux density. It can be shown [6] that HTS machines can be 2–5 times smaller in volume compared with conventional electrical machines for the same power. In addition, overall efficiency of the cryogenic HTS machines is expected to be higher than conventional machines. In this way, smaller and lighter motors can replace their conventional counterparts. This is very important for applications such as in land vehicles and in space aircrafts where volume and weight are to be kept at a minimum.

The great disadvantage of the ceramic HTS materials, in the construction of power devices, is its brittle nature and thus the difficulty to be machined. When using HTS materials in electrical machines, much care must be taken in the design of the rotors in order to eliminate mechanical stresses in these fragile materials. Perhaps reluctance rotors are the best candidates to employ these materials in their construction, and different configurations, giving different torques, are now considered.

## 2. The reluctance torque of a conventional motor

Fig. 1 shows the distribution of the flux density produced by the stator current in a conventional reluctance motor, obtained by means of a commercial finite element package (Flux 2D-Cedrat). The field produced by the stator is represented by the fundamental harmonic distributed current, reproducing a conventional two-pole, three-phase winding.

* Corresponding author. Address: Instituto Politécnico de Setúbal, Largo Defensores da República, 1, 2910-470 Setúbal, Portugal. Tel.: +351 265548820; fax: +351 265231110.
*E-mail address:* apires@est.ips.pt (A.J. Pires).

0921-4534/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2009.10.069

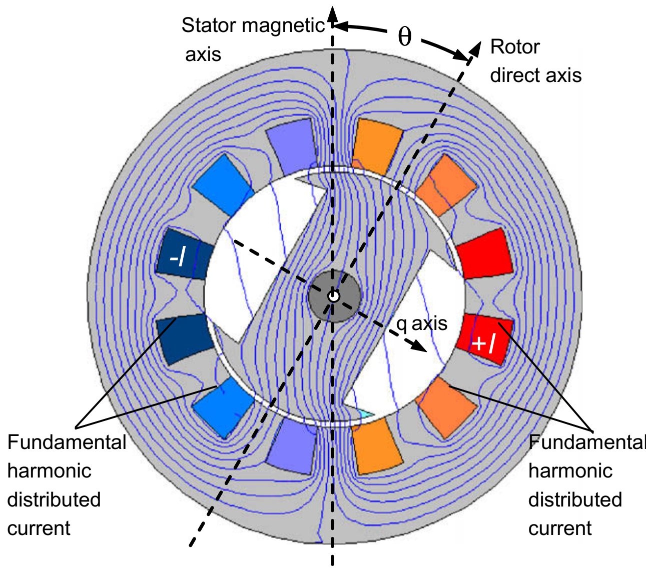


**Fig. 1.** Flux plot for a two-pole, three-phase conventional reluctance motor.

For this motor, torque is given by:

$$T = \frac{\partial W_{cm}}{\partial \theta} \tag{1}$$

where $\theta$ is the rotor position and $W_{cm}$ represents the magnetic co-energy of the system, which is given by (2), *valid for a single coil or a group of coils in the same axis*:

$$W_{cm} = \int_0^i \psi di \tag{2}$$

where $\psi$ represents the stator winding linking flux and $i$ the stator winding current.

Assuming absence of magnetic saturation, which is sufficient for this kind of analysis, a relation between $\psi$ and $i$ can be written as $\psi = L(\theta)i$, where $L(\theta)$ represents the stator winding inductance that depends on the rotor position, $\theta$. Therefore (2) reduces to (3)

$$W_{cm} = \frac{1}{2}L(\theta)i^2 \tag{3}$$

The salient type rotor, rotating around the stator, modulates the magnetic circuit permeance, $P(\theta)$, according to the rotor position, $\theta$. Consequently, the stator winding inductance, for a stator winding having $N$ turns, varies with rotor position according to

$$L(\theta) = N^2 P(\theta) \tag{4}$$

When the rotor direct axis is aligned with the stator magnetic axis ($\theta = 0$), the permeance is at a maximum and therefore the stator inductance attains the maximum value $L_{max}$.

On the other hand, when the rotor longitudinal axis is in quadrature with the stator magnetic axis ($\theta = \pi/2$), the stator inductance attains the minimum value $L_{min}$. For any rotor position, $\theta$, of the direct axis during a complete rotor revolution, and assuming sinusoidal variation for the magnetic circuit permeance and absence of magnetic saturation, the stator inductance versus rotor position, $L(\theta)$, which is modulated by the salient rotor, can be written, according to Fig. 2, as

$$L(\theta) = \frac{1}{2}(L_{max} + L_{min}) + \frac{1}{2}(L_{max} - L_{min})\cos(2\theta) \tag{5}$$

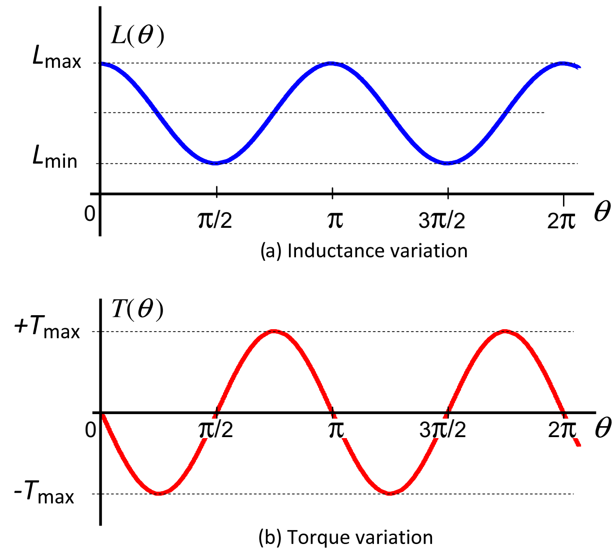


**Fig. 2.** Inductance and torque variation versus rotor position in a conventional reluctance motor.

Due to air-gap permeance variation, inductance has therefore two cycles in a complete rotor rotation, as shown plotted in Fig. 2a. For a round rotor, $L_{max} = L_{min} = L$, and Eq. (5) obviously simplifies to $L$.

The reluctance torque developed on the rotor shaft of this device with a constant r.m.s. current, $I$, through a single coil and according to (1) and (3) is given by relation

$$T(\theta) = \frac{1}{2}I^2 \frac{dL(\theta)}{d\theta} \tag{6}$$

For the three-phase reluctance motor case, and substituting (5) into (6), the reluctance torque is given by

$$T(\theta) = -\frac{3}{2}I^2(L_{max} - L_{min})\sin(2\theta) \tag{7}$$

This equation shows that the mean output torque motor along the electrical period is proportional to the well known relation $(L_{max} - L_{min})$ and describes also two cycles in one rotor revolution [7], as shown plotted in Fig. 2b.

According to Fig. 2b, the average torque is zero and the maximum torque value is attained for rotor positions, $\theta = \pi/4,\ 3\pi/4,\ 5\pi/4, \ldots$ In order to have a continuous rotation, an electronic commutation of the stator winding must be provided.

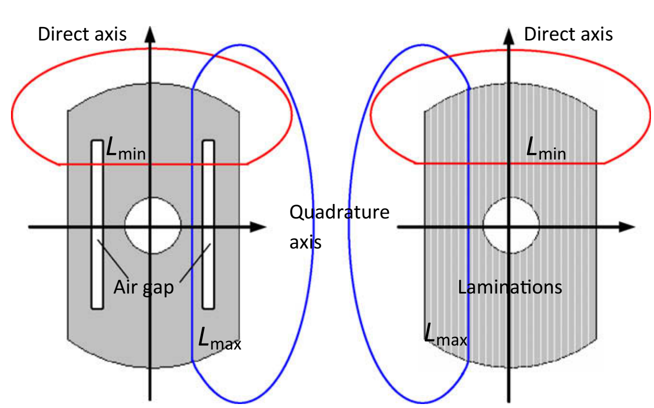


**Fig. 3.** Types of rotor flux barriers to decrease the quadrature axis flux.