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# SWITCHING FLUX PERMANENT MAGNET POLYPHASED SYNCHRONOUS MACHINES

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**Abstract :** This paper presents original structures of a permanent magnet synchronous polyphased machine with concentrated flux based on the switching flux principle. These machines are characterized by an association of elementary cells. The armature and the inductor are both located in the same part. The rotor is passive and has an important saliency. From the elementary cell, the authors describe several structures. Computation results are then presented. To make comparisons, all the machines have the same size. Computation has been done using a sinusoidal wave current having a density of  $5 \text{ A/mm}^2$  and ferrite permanent magnets. The first machine is characterized by a same tooth pitch on rotor and stator. In this case, the massic torque and stress shear are respectively  $1.7 \text{ Nm/kg}$  and  $1.18 \text{ N/cm}^2$ . In the second one, the tooth pitch on stator and rotor are different. The massic torque and stress shear are respectively  $1.97 \text{ Nm/kg}$  and  $1.37 \text{ N/cm}^2$ . A new PM arrangement is proposed. The performances of this new configuration are improved. The massic torque and stress shear are respectively  $3.62 \text{ Nm/kg}$  and  $3 \text{ N/cm}^2$ . The developed study on this machine has not only shown interesting performances but a possible working with constant power, having a theoretically infinite range of speed.

**Keywords :** Synchronous machine, Permanent magnet, flux weakening

## 1. Introduction

In this paper, we present new structures of synchronous polyphased machines with concentrated flux and permanent magnets. We notice that these structures are the same if we replace the magnets by excitation coils (this case has not been studied).

These new structures use the switching flux principle. Having a simple elementary structure, we give the rules to design a polyphased machine. For each studied machine, we present some essential characteristics (All the computations presented are made with 2D Finite Elements -F.E.2D- package [4]) such as the no-load flux form and the one of the electromagnetic torque. We also give an idea of possible performances supplying the massic torque and the stress shear. The first presented machines (type A1 & A2) are directly stemmed from an elementary cells juxtaposition. The symmetry of structure A2 and the better use idea of the available space has leaded us to define a new elementary structure (type B). The deduced polyphased machine permit close performances to the ones of other classical synchronous machines with buried magnets. We developed this machine study to know its working possibilities (no-load flux, detent torque, inductances, electromagnetic torque). This machine (type B), beside its passive rotor (active stator parts) and its robustness qualities made us able to obtain interesting performances (massic torque and stress shear). Associated with a voltage converter, this machine, even a voltage constraint, can workings with constant power, having a theoretically infinite range of speed ("flux weakening").

## 2. TYPE A MACHINE

In order to explain this principle, we present an elementary cell in figure 1. This contains one permanent magnet located between two "U" magnetic cores, an armature winding and a saliently rotor. On the first conjunction position (see figure 1a), the flux linkage induced by the PM is arbitrary positive. In the second conjunction

position (see figure 1b), this flux becomes negative. The design of a polyphased machine then needs the association of several of this elementary cell (see figure 2).

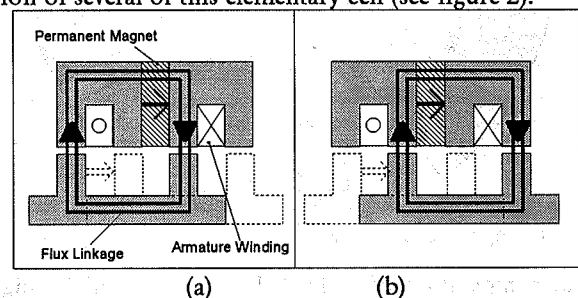


Fig. 1. The two conjunction positions

Different associations are possible considering several parameters such as :

- Number of phases  $q$
- Number of cells  $N_c$  per phase
- Angular stator width ( $\theta_s$ )
- Angular rotor width ( $\theta_r$ )

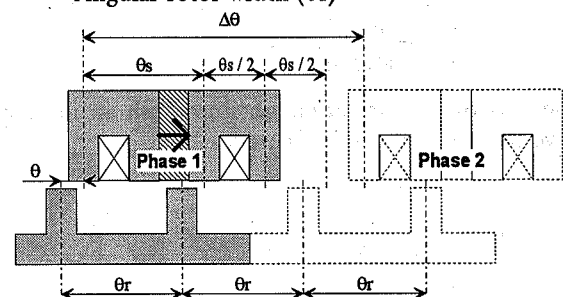


Fig. 2. Basic Schema of Polyphased Structure

From this elementary structure, there are two possibilities to design polyphased machines :

- i-  $\theta_r = \theta_s$  and  $\Delta\theta > 2\theta_s$  (Type A1 Machine)
- ii-  $\theta_r \neq \theta_s$  and  $\Delta\theta = 2\theta_s$  (Type A2 Machine)

### 2.1. Type A1 Machine

In this case, the angular stator width and the angular rotor width are the same. Also, in the conjunction posi-

tion, the flux crossing section is maximum. The successive cells are not magnetically coupled, this means that cells separated by a non-magnetic material. The angular shift  $\Delta\theta$  between two cells respects the following relations :

$$\Delta\theta = \frac{2\pi}{qN_c} \quad (1)$$

$$\theta_s = \theta_r = \frac{\Delta\theta}{2 \pm \frac{n}{q}} \quad (2)$$

An example of a three phase machine is shown in fig. 3. This machine is composed by six elementary cells and fourteen rotor poles ( $N_c = 2$  ;  $\pm n = 1$  ;  $q = 3$ ).

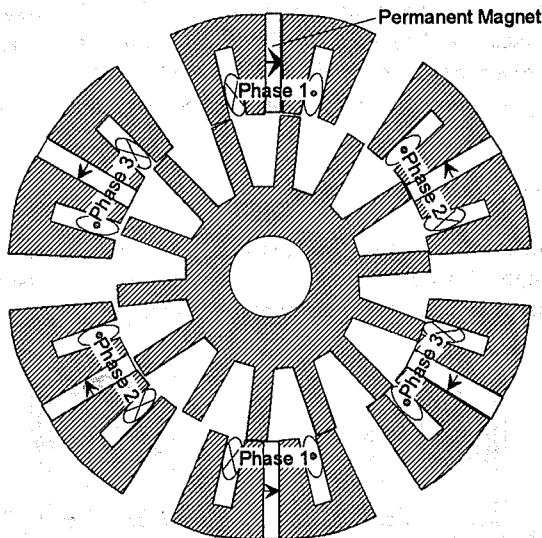


Fig. 3. Cross section of a type A1 three phased machine.

The computation of no-load flux, function of the angular position, is presented in figure 4.

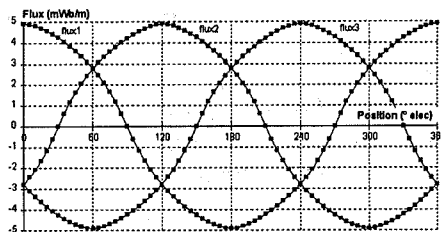


Fig. 4. No-load Flux (A1 type machine)

The electromagnetic torque obtained with an ideal sine wave current is shown in figure 5.

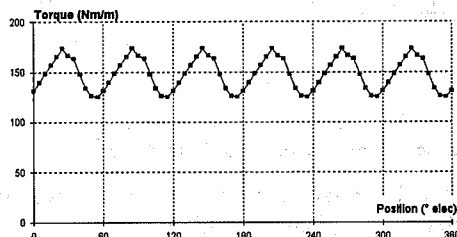


Fig. 5. Electromagnetic torque for ideal sine wave current (A1 type machine).

## 2.2. Type A2 Machine

For a type A2 machine, the angular stator width and the angular rotor one are different. The angular shift  $\Delta\theta$  between two cells respects the following relations :

$$\Delta\theta = \frac{2\pi}{qN_c} \quad (3)$$

$$\Delta\theta = 2\pi_{elec} \left( 2 \pm \frac{n}{q} \right) \text{ and } 2\pi_{elec} = \theta_r \quad (4)$$

$$\Rightarrow \theta_r = \frac{2\pi}{qN_c} \frac{1}{\left( 2 \pm \frac{n}{q} \right)} \quad (5)$$

$$\text{And } \theta_s = \frac{\Delta\theta}{2} \quad (6)$$

For a three phase machine ( $q = 3$ ) with two elementary cells per phase ( $N_c = 2$ ) we have :

$$\theta_r = \frac{2\pi}{10} \text{ and } \theta_s = \frac{2\pi}{12}$$

In the same conditions of A1 type machine, the no-load flux and the electromagnetic torque are respectively shown in figure 6 and 7.

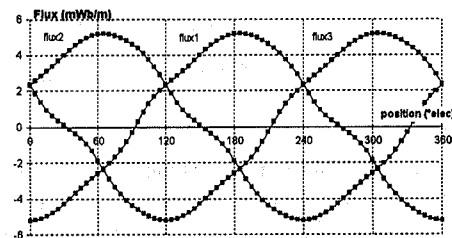


Fig. 6. No-load Flux (A2 type machine).

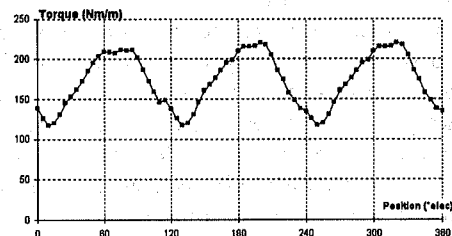


Fig. 7. Electromagnetic torque for ideal sine wave current (A2 type machine)

## 2.3. Numerical results

In the following, we present the intrinsic performances of both structures (A1 & A2), obtained for the same schedule conditions (see table 1).

Permanent magnet type	Ferrite $B_r = 0.4T$
External stator diameter	143 mm
Internal stator diameter	90 mm
Airgap length	0.35 mm
Winding coefficient	1
Current density	5 A/mm <sup>2</sup>

Table 1

The performances of both machines are close (See Table 2). Nevertheless, we observe an electromagnetic torque with a high ripple rate. This is mainly due to the important no-load flux harmonic rate and to the sine current supply mode. In order to solve such a problem, it is well known that one can precisely study the stator and rotor teeth shapes. In the following, and considering this problem, we conceived a switched flux polyphased synchronous machine that naturally have a sine wave no-load flux.

Machine type	A1	A2
No-load flux	5 mWb/m	5.2 mWb/m
Massic torque	1.7 Nm/kg	1.97 Nm/kg
Stress shear	1.18 N/cm <sup>2</sup>	1.37 N/cm <sup>2</sup>

Table 2.

On the basis of type A2 structure, which has stator cells separated by a space of same width of magnets, the spaces between stator cells of the new structure (type B) are made active by inserting magnets.

### 3. PRESENTATION OF TYPE B MACHINE

We can define a new elementary cell, presented in fig. 8.

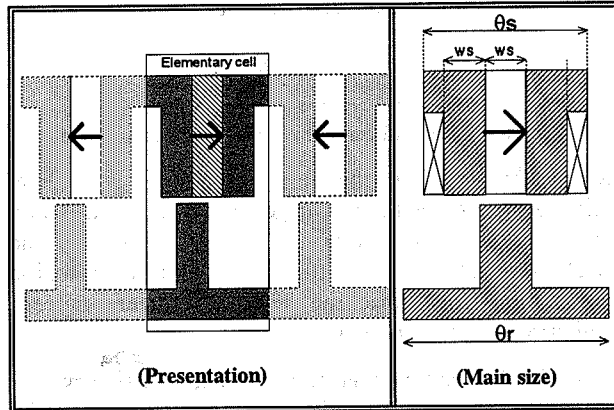


Fig.8. Elementary cell of a type B machine

#### 3.1. Electromagnetic sizing

As we have done for type A machines, we define the following parameters :

- $q$  : Number of phases
- $N_c$  : Number of cells per phase
- $\theta_s$  : Angular stator width
- $\theta_r$  : Angular rotor width
- $N_s$  : Number of stator teeth
- $N_r$  : Number of rotor teeth

The main relations to define a polyphased structure are:

$$N_r \theta_r = 2\pi \quad (7)$$

$$N_s \theta_s = 2\pi \quad (8)$$

$$\theta_s = \frac{2\pi}{q N_c} \quad (9)$$

$$\theta_s = 2\pi_{elec} \left( 1 \pm \frac{n}{2q} \right) \text{ and } \theta_r = 2\pi_{elec} \quad (10)$$

$$\Rightarrow \theta_r = \frac{\theta_s}{\left( 1 \pm \frac{n}{2q} \right)} \quad (11)$$

$$w_s = \frac{\theta_s}{4} \quad (12)$$

The main constraint for a resultant radial stress equal to zero imposes to have a even number of stator teeth ( $N_s$ ) and a even number of rotor teeth ( $N_r$ ).

In figure 9, we present an example of three phase machine with :

$$q = 3 ; N_c = 4 ; N_s = 12 ; N_r = 10.$$

This example corresponds to a machine that minimizes, for a given speed, the electrical frequency. Furthermore, for facility construction reasons, the stator is made of a unique part. This generates a short-circuit of magnets. Nevertheless, the saturation of upper magnets' parts permit a moderated decrease of performances comparatively to a no short-circuit solution (10%).

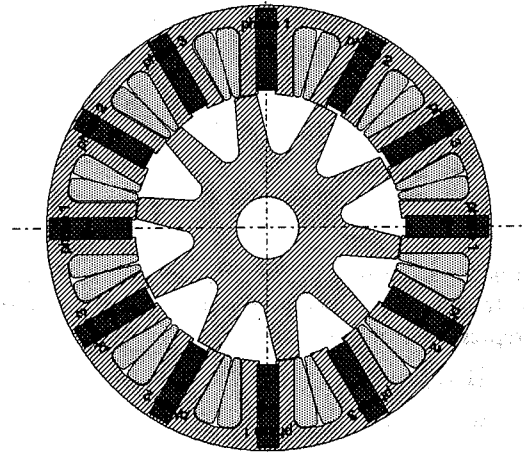


Fig. 9. Cross section of a three phase machine of type B.

#### 3.2. Numerical results

The main sizes of type B machine are given in table 3.

Permanent magnet type	Ferrite $B_r = 0.4T$
External stator diameter	143 mm
Internal stator diameter	86 mm
Airgap length	0.35 mm
Winding coefficient	1
Current density	5 A/mm <sup>2</sup>

Table 3

##### 3.2.1. No - load characteristics

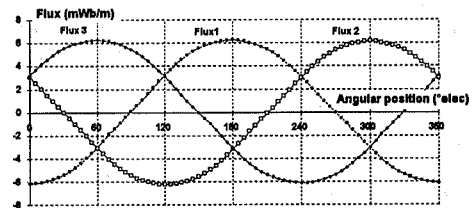


Fig. 10. No-load flux

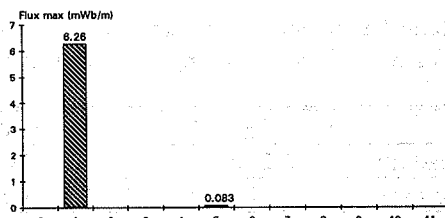


Fig. 11. Frequency spectrum of the no-load flux

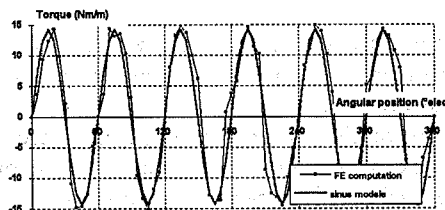


Fig. 12. Permanent magnet detent torque

### 3.2.2. Inductances waveform.

Despite the salient rotor necessary to a switching flux, the inductances have small variations (see Fig 13). The d-axis and the q-axis inductances can be considered as constant (see Fig. 14).

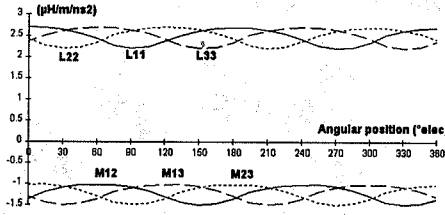


Fig. 13. Self and Mutual Inductances

To calculate the d- and q-axes inductances, we use the Park transform. Inductances obtained by (13) relation are represented in figure 14.

$$(L)_{dq} = (P)(L)_{abc}(P)^{-1} \quad (13)$$

With (P) is Park matrix.

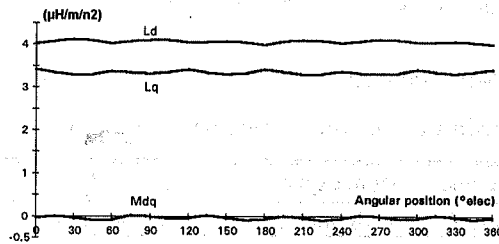


Fig. 14. Inductances in d-q axes.

### 3.2.3. Power capability at low speeds

In order to estimate the power capability at low speed of the machine, we have calculate the electromagnetic torque for ideal sine wave current and it is represented in the figure 15.

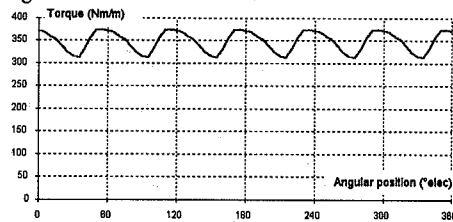


Fig. 15. Electromagnetic torque for ideal sine wave current

The obtained electromagnetic performances are given in table 4 for two values of winding coefficient ( $k_b$ ).

	$k_b = 1$	$k_b = 0.5$
No-load flux	6.2 mWb/m	6.2 mWb/m
Massic torque	3.62 Nm/kg	1.81 Nm/kg
Stress shear	3 N/cm <sup>2</sup>	1.5 N/cm <sup>2</sup>

Table 4

Comparatively to type A machines, we have an increase of 1.8 with regard to massic torque and a one of 2 with regard to stress shear.

We also notice that the obtained performances, for a realistic winding coefficient, are close to the ones of classical buried magnet synchronous machines.

### 3.2.4. Power capability at high speeds

#### 3.2.4.1. Presentation

In this part, our main interest goes to the energy conversion possibilities of the machine (type B) associated to a current regulated power converter. the principle scheme is given in figure 16.

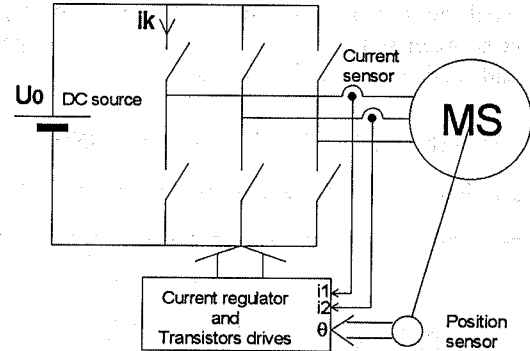


Fig. 16. Diagram of current regulated - machine drive

We notably examine the power capability of the machine associated with a voltage converter. This study considers the limited voltage of the DC source or the breakdown voltage of the transistors, and the machine constraints (global machine heat i.e. efficient current limitation at lower speeds).

#### 3.2.4.2. Torque calculated using d-q axis theory

Using the classical d-q axis theory, we determine the components of current which give constant power capability to infinite speed (losses neglected).

$$I_d = I \cos \beta \quad (14)$$

$$I_q = I \sin \beta \quad (15)$$

$$V_d = r I_d - X_q I_q \quad (16)$$

$$V_q = r I_q + X_d I_d + E \quad (17)$$

$$E = \sqrt{\frac{3}{2}} \psi_m \omega = \psi_d \omega \quad (18)$$

$$P_{abs} = (r I_d - X_q I_q) I_d + (r I_q + X_d I_d + E) I_q \quad (19)$$

$$\Rightarrow P_J = r(I_d^2 + I_q^2) \quad (20)$$

$$\Rightarrow C = \psi_d I_q + p(L_d - L_q) I_d I_q \quad (21)$$

In fact, this machine has a very high capacity of "flux weakening". The ration " $L_d I / \psi_d$ ", is largely higher than one for a current density of 5 A/mm<sup>2</sup>, where  $L_d$  is the d-axis inductance,  $I$  is the rated current and  $\psi_d$  is the d-axis magnet flux-linkage.

As we can see in figures 17-18, there are three functioning zones.

- At low speeds ( $N < 3000$  rpm), the torque is maximum, the current is limited ( $I_{eff} = k_b \delta S_{bob}$ )

and the current angle ( $\beta \approx 90^\circ$ ) is optimal for maximum torque.

② For higher speeds than the rated speed ( $N = 3000$  rpm), the maximum torque is obtain with the limited current and with increasing current angle above  $90^\circ$  ( $\beta \nearrow$  and  $I_{\text{eff}} = k_b \delta S_{\text{bob}}$ ).

③ Beyond near the double rated speed ( $N = 6500$  rpm), to have a maximum output power, the current angle must increasing but the current must decreasing under the limited current.

With  $k_b$  = winding coefficient,  $\delta$  = current density and  $S_{\text{bob}}$  = winding area.

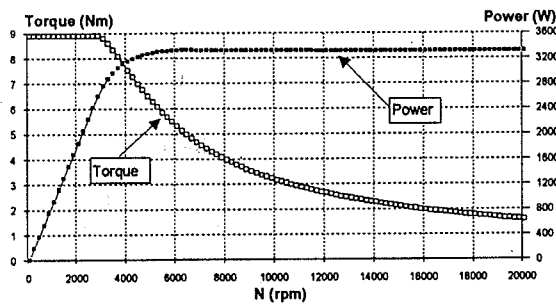


Fig. 17. Calculated flux weakening performance.

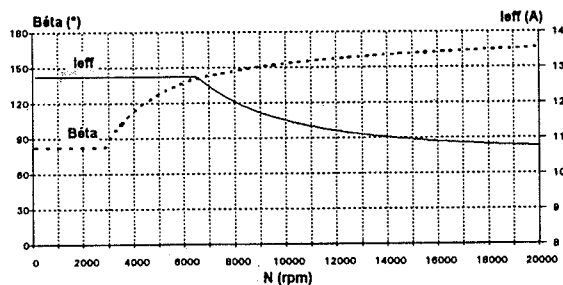


Fig. 18. Operating characteristics at maximum power output.

In order to have a constant power region, and because this machine has a high capability of flux weakening, at high speeds, the current decreases (copper losses too). The other losses (mechanical and iron) were computed and they increase with speed but the efficiency remains higher than 95 %.

#### 4. CONCLUSION

This paper presents original structures of a permanent magnet synchronous polyphased machine based on the switching flux principle and with concentrated flux. The armature and the inductor are both located in the stator. Intrinsic performances obtained, without sizing studies, are very encouraging. We start to present the elementary cell and the switching flux principle. Later on, we present three PM synchronous three phase machines with their intrinsic characteristics. The performances of this new configuration are improved. The massic torque and stress shear are respectively 3.62 Nm/kg and 3 N/cm<sup>2</sup>. The developed study of a machine with interesting performances permitted working possibilities at constant power with a theoretical infinite range of speed.

#### 5. APPENDIX

##### Voltage converter

DC voltage (V)	E	300
Imax converter (A)	$I_m$	18
Phase voltage max (V)	$V_{am}$	150
Phase voltage eff (V)	$V_{a\text{eff}}$	106
Phase current eff (A)	$I_{\text{eff}}$	12.7

##### Type B Machine

Rated speed (rpm)	N	3000
Active length (m)	$l_a$	0.05
Number of turn	$n_s$	104
Winding area (mm <sup>2</sup> )	$S_{\text{bob}}$	530
Winding coefficient	$k_b$	0.5
Magnet Flux-linkage (Wb)	$\psi_m$	0.033
Phase resistor ( $\Omega$ )	r	0.082
d-axis inductance (mH)	$L_d$	2.19
q-axis inductance (mH)	$L_q$	1.92
Current density (A/mm <sup>2</sup> )	d	5.00
Flux weakening ratio (Rdf)	$L_d I_{\text{eff}} / \phi_m$	1.21

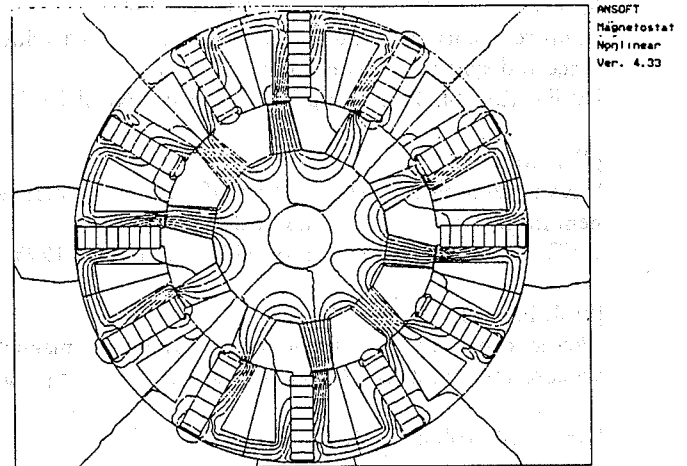


Fig.19. Flux distribution in no-load (P M only)

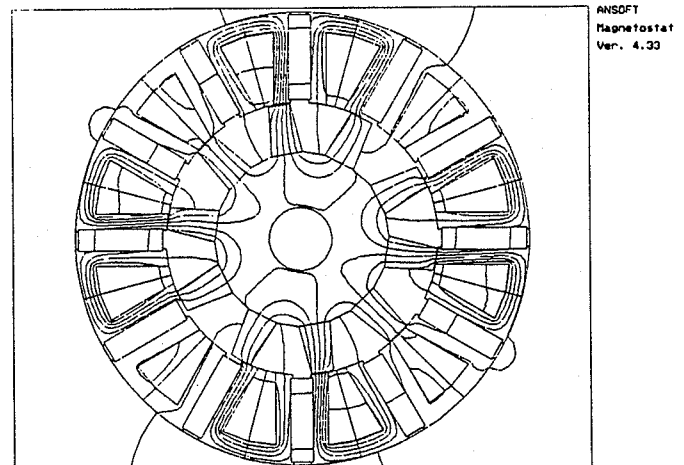


Fig.20. Flux distribution driven by the d-axis current

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