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Analysis of 3-D Effects in Segmented Cylindrical Quasi-Halbach Magnet Arrays

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To improve the performance of permanent magnet (PM) machines, quasi-Halbach PM arrays are used to increase the magnetic loading in these machines. In tubular PM actuators, these arrays are often approximated using segmented magnets resulting in a 3-D magnetic field effect. This paper describes the results of this segmentation obtained from an analytical model. The influence of the number of segments on the magnetic flux density in the air gap is investigated for several actuator dimensions. Furthermore, the effect of this segmentation on the mean value of the radial component of the flux density over the circumference of the cylindrical air gap is analyzed and a 2-D definition of this effect is given. A general rule is presented as a table showing the decrease of the magnetic field as function of the design parameters.

Index Terms—Halbach array, magnetic field modeling, permanent-magnet, ring magnet, tubular actuators.

I. INTRODUCTION

TODAY, the need for efficient actuators with high force density in industrial applications is rapidly growing. As permanent magnet (PM) actuators have a high efficiency and high force density, this class of actuators is widely used. In literature, the subject of the design of PM magnet actuators with various PM configurations is extensively described. For example, Halbach structures are used to enhance the power density [1]–[3]. Due to the evolution of materials and production techniques, PMs in various shapes emerge and the approximation of an ideal Halbach magnetization improves [4], [5].

One particular class where Halbach magnet arrays are exploited is the tubular permanent magnet actuator (TPMA). This class of cylindrical linear machines has the advantages of no end-windings and no net attraction force [6]. Due to the absence of the end-windings, an important loss factor in linear machines is eliminated and a very high force density can be achieved. In literature, several papers describe tubular permanent magnet actuators with quasi-Halbach magnetization, as shown in Fig. 1. To avoid an expensive single PM with sinusoidal magnetization (i.e., ideal Halbach), quasi Halbach is often used to exploit the high field densities produced by an Halbach array. In TPMAs, quasi Halbach permanent magnet arrays consist of axial and radial magnetized ring magnets.

To produce the radial magnetized magnet ring of the quasi-Halbach magnet array, essentially two approaches are possible [7]. Using a geometric-specific impulse magnetizing fixture as presented in [8], a compression-molded bonded magnet ring can be produced as a single shape component what can be advantageous in certain applications. The second approach results in a compound magnet; the ring magnet is approximated by diametrically magnetized segments as shown in Fig. 2(c), (d). This segmented PM results in a 3-D effect which reduces the effective radial component of the flux density. Therefore, during design

Fig. 1. Quasi-Halbach magnet array of a tubular permanent magnet actuator having radial ring magnets consisting of diametrically magnetized segments.

Fig. 2. (a) Cylindrical quasi Halbach magnet array, (b) ideal radial magnetized ring magnet, (c) and (d) approximated radial magnetized ring magnets.

of a TPMA, the number of segments has to be taken into account while calculating the performance of the actuator. For the calculation of the exact magnetic field distribution in an actuator with segmented ring magnets, a 3-D analysis is required. To date, most papers describing tubular actuators with Halbach magnetization consider the 2-D problem with perfect radial magnetized magnets [5], [9].

In [10], the approximation by diametrically magnetized segments is mentioned for a ring magnet containing six segments. Results from a 3-D finite element analysis are presented showing a slight increase of the radial component of the flux density for the segmented ring. In the conclusions the authors

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state that although the ring magnet is approximated by diametrically magnetized segments, the measurements show good agreement with the analysis which was based on ideal ring magnets.

Previously, the authors of this paper presented a 3-D model which provides the magnetic field expression for the segmented quasi-Halbach array [11]. The goal of the current paper is to extend the model and to investigate the effects of the segmentation of the radial ring magnet on the performance of the actuator. As the 3-D model is rather complex and time-consuming to create and implement, a simplified model is of importance in a design tool of a tubular actuator. Therefore, a 2-D approximation of the complex 3-D model is developed and presented. Using this simplified model, the effect of segmentation on the performance of the actuator can be calculated. The circumferential field component that arises from the segmentation cannot be calculated by this model, however, in general this field component does not affect the performance of the TPMA.

To avoid the necessity of creating a model to investigate the segmentation effect during the design of a TPMA, an analysis is performed to obtain the influence of each geometric design parameter on the effect of segmentation. In the analysis, four different topologies of the TPMA are analyzed in all ranges of dimensions. The influence of the different geometric parameters of the TPMA on the effect of the segmentation is investigated. The last section of this paper presents the results of this analysis as well as a table containing a general rule that can be used while selecting the number of segments.

II. MODELING

To be able to compare the performance with an actuator without segmented ring magnets, two models are created. The magnetic flux density in the air gap is calculated and compared. The 3-D segmented model is described in [11], and the 2-D ideal model in [12].

In both semi-analytical models, the sources and resulting fields are described by a Fourier series by solving the magneto-static Maxwell equations. The solution of the Maxwell equations are obtained using the magnetic scalar potential. The main disadvantage of φ is that it can be applied only in current free problems, however, this paper investigates only the magnetic field due to the permanent magnets, and hence, the model is current free. A major advantage of φ is the reduced complexity in 3-D problems. The magnetic vector potential will result in a vector with three components each a function of r, z, θ , while the magnetic scalar potential is a single scalar function of r, z, θ . Therefore, the magnetic scalar potential is used which is defined as

$$\vec{H} = -\nabla\varphi. \quad (1)$$

In the model, the following assumptions are made:

- 1) the soft-magnetic parts are infinitely permeable;
- 2) the cylinder is infinitely long, the end-effects are not taken into account;
- 3) the permanent magnets have a linear demagnetization characteristic;

- 4) all regions are nonconducting and current-free.

The scalar potential has to be solved in the source free regions, I and III, and in the permanent magnet region II, as shown in Fig. 2(a). In the latter region this results in the Poisson equation (2), and in region I and III in the Laplace equation (3)

$$\nabla^2\varphi = \frac{1}{\mu_r} \nabla \cdot \vec{M}, \quad (2)$$

$$\nabla^2\varphi = 0 \quad (3)$$

where μ_r is the relative permeability of the permanent magnets and $\vec{M}$ is the magnetization vector describing the magnet array by means of a Fourier series.

A. Magnetization

1) *Ideal Ring Magnet*: The magnetization of the quasi-Halbach magnet-array with the ideal radial PM ring as shown in Fig. 2(b) consists of a radial and an axial component as function of the axial position. Because the magnetization does not have dependency in the circumferential direction, the magnetic field distribution is two dimensional and the magnetization vector is given by

$$\vec{M}(z) = M_r\vec{e}_r + M_z\vec{e}_z \quad (4)$$

where $\vec{e}_r, \vec{e}_z$ are the unit vectors in the radial and axial direction respectively. Both components of the magnetization are described by an infinite Fourier series

$$M_r(z) = \frac{B_{\text{rem}}}{\mu_0} \sum_{k=1}^{\infty} M_{rk} \sin(mz) \quad (5)$$

$$M_z(z) = \frac{B_{\text{rem}}}{\mu_0} \sum_{k=1}^{\infty} M_{zk} \cos(mz) \quad (6)$$

where B_{rem} is the remanent flux density of the permanent magnets, μ_0 the permeability of air, and $m = k\pi/\tau_z$ are the spatial frequencies as a function of harmonic number k . The harmonic components M_{rk} and M_{zk} to describe the square wave as shown in Fig. 2(a) are defined as

$$M_{rk} = \frac{4}{k\pi} \sin\left(\frac{\tau_{mr}k\pi}{2\tau_z}\right) \sin\left(\frac{k\pi}{2}\right) \quad (7)$$

$$M_{zk} = \frac{4}{k\pi} \cos\left(\frac{\tau_{mr}k\pi}{2\tau_z}\right) \sin\left(\frac{k\pi}{2}\right). \quad (8)$$

2) *Segmented Ring Magnet*: Where the quasi-Halbach magnet array with an ideal ring magnet can be described by a 2-D magnetization vector, with the introduction of the segmented ring magnets, the magnetization vector becomes 3-D. As can be seen in Fig. 2(c) and (d), the segments introduces besides the radial component, a circumferential component in the magnetization vector. Therefore, the magnetization vector needs to be rewritten to

$$\vec{M}(z) = M_r\vec{e}_r + M_z\vec{e}_z + M_\theta\vec{e}_\theta. \quad (9)$$

To describe this magnetization analytically, a two-dimensional Fourier analysis is used resulting in the following expressions:

$$M_r(\theta, z) = \frac{B_{rem}}{\mu_0} \sum_{n=0}^{\infty} M_{rn} \cos(w\theta) \sum_{k=1}^{\infty} M_{rk} \sin(mz) \quad (10)$$

$$M_\theta(\theta, z) = \frac{B_{rem}}{\mu_0} \sum_{n=0}^{\infty} M_{\theta n} \sin(w\theta) \sum_{k=1}^{\infty} M_{\theta k} \sin(mz) \quad (11)$$

$$M_z(\theta, z) = \frac{B_{rem}}{\mu_0} \sum_{n=0}^{\infty} M_{zn} \cos(w\theta) \sum_{k=1}^{\infty} M_{zk} \cos(mz) \quad (12)$$

where $w = n\pi/\tau_\theta$ is the spatial frequency in the circumferential direction as a function of harmonic number n . As the radial and the axial component of the magnetization in the circumferential direction have a DC-component, the Fourier description starts with $n = 0$.

The spatial frequency in the circumferential direction has a fundamental period of $2\tau_\theta$, as defined in Fig. 2(c) and (d). This pole pitch τ_θ is defined by the number of segments of a the ring magnet by $\tau_\theta = 2\pi/N_s$, where N_s is the number of segments. This definition results in the following expressions for the Fourier coefficients for the circumferential direction as function of the number of segments N_s

$$M_{rn} = \begin{cases} \frac{-8\pi \cos\left(\frac{n\pi}{2}\right)^2 (-1)^n \sin\left(\frac{\pi}{N_s}\right)}{N_s \left(n^2\pi^2 - \left(\frac{2\pi}{N_s}\right)^2\right)} & \text{for } n \neq \frac{2}{N_s} \\ 0 & \text{for } n = \frac{2}{N_s} \\ \frac{N_s \sin\left(\frac{\pi}{N_s}\right)}{\pi} & \text{for } n = 0 \end{cases} \quad (13)$$

$$M_{\theta n} = \begin{cases} \frac{4n\pi \cos\left(\frac{n\pi}{2}\right)^2 \sin\left(\frac{\pi}{N_s}\right)}{n^2\pi^2 - \left(\frac{2\pi}{N_s}\right)^2} & \text{for } n \neq \frac{2}{N_s} \\ 0 & \text{for } n = \frac{2}{N_s} \\ 0 & \text{for } n = 0 \end{cases} \quad (14)$$

$$M_{zn} = \begin{cases} 0 & \text{for } n \neq 0 \\ 1 & \text{for } n = 0 \end{cases} \quad (15)$$

The Fourier coefficients for the axial direction are the same as for the ideal ring magnet

$$M_{rk} = \frac{4}{k\pi} \sin\left(\frac{\tau_{mr}k\pi}{2\tau_z}\right) \sin\left(\frac{k\pi}{2}\right) \quad (16)$$

$$M_{\theta k} = \frac{4}{k\pi} \sin\left(\frac{\tau_{mr}k\pi}{2\tau_z}\right) \sin\left(\frac{k\pi}{2}\right) \quad (17)$$

$$M_{zk} = \frac{4}{k\pi} \cos\left(\frac{\tau_{mr}k\pi}{2\tau_z}\right) \sin\left(\frac{k\pi}{2}\right) \quad (18)$$

The corresponding waveforms of the magnetization as function of the axial position are shown in Fig. 3. Because the radial and the circumferential component of the magnetization originate from the same magnet, the waveforms coincide while the magnetization in the axial direction is zero for nonzero radial or circumferential magnetization.

In Fig. 4, the magnetization as function of the circumferential direction is shown for different number of segments. As the

Fig. 3. Radial, tangential and axial magnetization vector of a Quasi-Halbach magnetization pattern with segmented radially magnetized ring magnets.

Fig. 4. Magnetization components in the radial and the circumferential direction for a ring magnet consisting of (a) two segments, (b) three segments, (c) six segments.

axial component is independent of the circumferential direction as given in (15), this component is not shown in the figures. In Fig. 4(a), the magnetization is shown when the ring magnet is approximated using two segments, Fig. 4(b) shows the magnetization when three segments are used and Fig. 4(c) shows the magnetization having six segments. As can be seen, increasing the number of segments reduces the ripple in the radial magnetization and decreases the magnetization in the circumferential direction.

B. Magnetic Field Description

Using the magnetization description for the ideal ring magnet and the segmented ring magnet as given in the previous section, an expression for the magnetic scalar potential is found by solving (2) and (3) [11]. This results in a 2-D solution for the ideal radial magnetized ring magnet, which is in the air gap

$$\varphi_{2D}(r, z) = \sum_{k=1}^{\infty} -\frac{1}{m} (a_k \mathcal{I}_0(mr) + b_k \mathcal{K}_0(mr)) + G_r(r) + G_z(r) \sin(mz) \quad (19)$$

where the coefficients a_k , b_k , can be found by solving the boundary conditions of the model and where

$$G_r(r) = -\frac{mM_{rk}B_{rem}}{\mu_0\mu_r} \left(\mathcal{I}_0(mr) \int_{R_r}^r \mathcal{K}_0(m\nu) d\nu - \mathcal{K}_0(mr) \int_{R_r}^r \mathcal{I}_0(m\nu) d\nu \right) \quad (20)$$

$$G_z(r) = \frac{m^2 M_{zk} B_{rem}}{\mu_0\mu_r} \left(\mathcal{I}_0(mr) \int_{R_r}^r \nu \mathcal{K}_0(m\nu) d\nu - \mathcal{K}_0(mr) \int_{R_r}^r \nu \mathcal{I}_0(m\nu) d\nu \right) \quad (21)$$

$$\varphi_{3D}(r, \theta, z) = \sum_{n=0}^{\infty} \sum_{k=1}^{\infty} -\frac{1}{m} (a_{nk} \mathcal{I}_w(mr) + b_{nk} \mathcal{K}_w(mr)) + G_r(r) + G_z(r) + G_{\theta}(r) \times \cos(w\theta) \sin(mz) \quad (22)$$

$$G_r(r) = -\frac{mM_{rk}M_{rn}B_{rem}}{\mu_0\mu_r} \times \left(\mathcal{I}_w(mr) \int_{R_r}^r \mathcal{K}_w(m\nu) d\nu - \mathcal{K}_w(mr) \int_{R_r}^r \mathcal{I}_w(m\nu) d\nu \right) \quad (23)$$

$$G_z(r) = \frac{mmM_{zk}M_{zn}B_{rem}}{\mu_0\mu_r} \times \left(\mathcal{I}_w(mr) \int_{R_r}^r \nu \mathcal{K}_w(m\nu) d\nu - \mathcal{K}_w(mr) \int_{R_r}^r \nu \mathcal{I}_w(m\nu) d\nu \right) \quad (24)$$

$$G_{\theta}(r) = -\frac{wmM_{\theta k}M_{\theta n}B_{rem}}{\mu_0\mu_r} \times \left(\mathcal{I}_w(mr) \int_{R_r}^r \mathcal{K}_w(m\nu) d\nu - \mathcal{K}_w(mr) \int_{R_r}^r \mathcal{I}_w(m\nu) d\nu \right) \quad (25)$$

which are nonzero only in the magnet region.

TABLE I
MODEL PARAMETERS

Property	Value	Description
B_{rem} (T)	1.2	Remanent flux density of PM
μ_r	1.05	Relative permeability of PM
R_r (mm)	15.0	Magnet inner radius
R_m (mm)	22.0	Magnet outer radius
R_i (mm)	23.0	Iron inner radius
τ_z (mm)	20.0	Pole pitch in axial direction
$\frac{\tau_{mr}}{\tau_z}$	0.45	Radial magnet to pole pitch ratio
N_s	3	Number of segments of ring magnet
τ_{θ} (mm)	$\frac{2\pi}{3}$	Pole pitch in angular direction
N	27	Number of harmonics in angular direction
K	20	Number of harmonics in axial direction

Fig. 5. Radial component of the flux density in the middle of the air gap for a quasi-Halbach cylinder having radial ring magnets consisting of three segments for the dimensions as given in Table I.

For the segmented ring magnets, a 3-D expression for the magnetic scalar potential is found, which is given by (22), where G_r , G_z , G_{θ} are only nonzero in the magnet region. The solution for the magnetic field components can be found using the definition of the magnetic scalar potential (1). In [11], the results of the 3-D model are verified with finite element analyses.

III. RESULTS

To show the effect of the segmentation of the radial magnet, a model is created having the dimensions as listed in Table I. Using the 3-D model, a surface plot is created of the radial component of the flux density in the middle of the air gap as shown in Fig. 5. As can be seen, the ring magnet consists of three segments represented by the three peaks.

To investigate the influence of this segmentation on the performance of a tubular actuator, the radial component of the flux density in the center of the air gap is compared to the flux density of a quasi-Halbach cylinder having ideal radially magnetized magnets. In a (nonskewed) tubular actuator, the coils have a cylindrical shape and are located at a constant axial position. Hence, the flux seen by the coils can be represented as the mean value of the field in the circumferential direction. Therefore, the mean value of the radial component of the flux density in the circumferential direction is calculated from the 3-D field solution and shown in Fig. 6. Using the 2-D model, the radial component of the flux density in the air gap is calculated as well and represented in Fig. 6 as function of the axial position.

Fig. 6. Radial component of the flux density in the middle of the air gap for a quasi-Halbach cylinder having radial ring magnets consisting of three segments, and a quasi-Halbach cylinder having ideal radially magnetized magnets for the dimensions as given in Table I.

Fig. 7. Harmonic analysis of the results presented in Fig. 6 (ring magnet having three segments) and the difference in the field components between the ideal and the segmented magnetized magnets.

As can be seen, the peak value of the radial component of the flux density for the quasi-Halbach cylinder having segmented radial magnets is lower than the one having ideal radially magnetized magnets. In Fig. 7, the harmonics of the radial component of the flux density are shown for the two cases as well as the difference between the two values. The first harmonic of the flux density of the segmented model is 7% lower while the third harmonic is 50% lower. As can be seen, the 13th and the 17th harmonic are higher for the cylinder having segmented magnets.

IV. 2-D MODEL

Instead of calculating the mean value of the 3-D field distribution in the air gap as presented before, this section will derive a 2-D model describing the effect of the segmentation on the mean value of the flux density in the air gap. To obtain the 2-D solution, the 3-D expression for the magnetic scalar potential is integrated in the circumferential, θ , direction

$$\varphi(r, z) = \frac{1}{2\pi} \int_0^{2\pi} \varphi_{3D}(r, \theta, z) d\theta \quad (26)$$

$$= \frac{1}{2\pi} \int_0^{2\pi} \sum_{n=0}^{\infty} \sum_{k=1}^{\infty} f_1(r, n, k) f_2(\theta, n, k) \times f_3(z, n, k) d\theta \quad (27)$$

where

$$f_1(r, n, k) = a_{nk} \mathcal{I}_w(mr) + b_{nk} \mathcal{K}_w(mr) + G_r(r) + G_z(r) + G_\theta(r) \quad (28)$$

$$f_2(\theta, n, k) = \cos(w\theta) \quad (29)$$

$$f_3(z, n, k) = -\frac{1}{m} \sin(mz). \quad (30)$$

Because the integral of $f_2(\theta, n, k)$ in (27) is only nonzero for $n = 0$, the sum over n disappears and because the other terms are not a function of the circumferential position θ , (27) results in

$$\varphi(r, z) = \sum_{k=1}^{\infty} f_1(r, 0, k) f_3(z, 0, k) \quad (31)$$

$$= \sum_{k=1}^{\infty} -\frac{1}{m} (a_k \mathcal{I}_0(mr) + b_k \mathcal{K}_0(mr) + G_r(r)|_{n=0} + G_z(r)|_{n=0} + G_\theta(r)|_{n=0}) \times \sin(mz). \quad (32)$$

Rewriting the function $G_{...}(r)$ results in the following equations:

$$G_r(r)|_{n=0} = -\frac{mM_0M_{rk}B_{rem}}{\mu_0\mu_r} \times \left(\mathcal{I}_0(mr) \int_{R_r}^r \mathcal{K}_0(m\nu) d\nu - \mathcal{K}_0(mr) \int_{R_r}^r \mathcal{I}_0(m\nu) d\nu \right) \quad (33)$$

$$G_z(r)|_{n=0} = \frac{m^2M_{zk}B_{rem}}{\mu_0\mu_r} \times \left(\mathcal{I}_0(mr) \int_{R_r}^r \nu \mathcal{K}_0(m\nu) d\nu - \mathcal{K}_0(mr) \int_{R_r}^r \nu \mathcal{I}_0(m\nu) d\nu \right) \quad (34)$$

$$G_\theta(r)|_{n=0} = 0 \quad (35)$$

where

$$M_0 = \frac{N_s \sin\left(\frac{\pi}{N_s}\right)}{\pi}. \quad (36)$$

Consequently, the model can be reduced to a 2-D model with the same magnetic scalar potential expression as given in (19) with only a single scaling factor in $G_r(r)$. The only drawback is that the circumferential component of the flux density is not taken into account in this model. However, to investigate the influence on the radial component of the flux density, which

TABLE II
ACTUATOR DIMENSIONS FOR ANALYSIS

Parameters	Design 1	Design 2	Design 3
R_r (mm)	2.0	20.0	19.5
R_m (mm)	6.0	30.0	24.5
R_i (mm)	8.0	31.0	25.5
τ_z (mm)	8.5	20.0	10.0
$\frac{\tau_{mr}}{\tau_z}$	0.4	0.5	0.6

produces the effective force in a tubular permanent actuator, this model is very suitable.

V. ANALYSIS

To be able to obtain a general rule to describe the effect of the segmentation on a given actuator, a parametric sweep on the main design parameters is performed. The design parameters of three actuators with different sizes are used as basis. The first actuator is a small slotless actuator designed for high acceleration applications having no back-iron on the moving part. Design 2 is presented in [10], this slotted actuator has also no back-iron in the mover. The last analyzed actuator is based on the design rules presented in [13] and has a soft-magnetic support tube which acts as back-iron for the magnetic mover. The dimensions of the actuators are given in Table II.

The three actuator designs are modeled using the models described above. To compare the performance of an actuator equipped with ideal ring magnets with one having segmented magnets, the first, third, fifth, and seventh harmonic are compared. The difference in the mean value of the radial component flux density over the circumference is calculated for magnets having different number of segments. The results of this analysis are shown in Fig. 8(a)–(c). The absolute value of flux density for the given harmonic is given above the figure.

As can be seen, the value of most harmonics is decreased due to the segmentation. However, the fifth harmonic of design 1 and third harmonic of design 3 show a slightly increased value. The third harmonic of design 2 shows a much higher positive difference when a few segments are used to approximate the magnet. However, the absolute value of this third harmonic is only 0.008 T compared to 1.28 T of the first harmonic, hence, the absolute effect of this harmonic on the performance of this actuator is very small.

A. Generalized Results

The segmentation has a different effect on each design, as can be seen, when a small number of magnets is used to approximate the ring magnet, the first harmonic of design 3 is more affected than the first harmonic of design 1. To find which design parameter affects the segmentation effect the most, the design parameters as presented in Table II are one by one varied and the results are compared. Besides the designs presented in Table II, a wide range of other dimensions are investigated, from small to very large actuators.

To quantify the effect of the segmentation, the minimum number of segments required to have less than 1%, 3%, and 5% reduction of the first harmonic of the flux density in the center

Fig. 8. Difference in the mean value of the radial component of the flux density in the air gap between an ideal and a segmented ring magnet for the actuators presented in Table II. The results are shown per harmonic for several number of segments. The absolute value of the radial flux density in case of an ideal ring magnet is given above each figure. (a) Design 1; (b) design 2; (c) design 3.

of the air gap is calculated. From this analysis the conclusion can be drawn that the influence of one parameter is more significant than the other parameters, namely, the ratio between the normal and the tangential magnetized magnet. As presented in the preceding section, the segmentation can be modeled as a decreased magnetization of only the normal magnetized magnets. Hence, the effect of the ratio between the normal and tangential magnetized magnets is consistent.

As the other parameters have a smaller effect, generalized results are obtained and presented in Table III. Four different topologies are investigated. In general, the Halbach magnetization has self-shielding properties, [2], and hence, no back-iron is required below the magnet array. However, applying back-iron can enhance the magnetic field in the actuator, therefore, this topology is investigated as well. Fig. 2 shows a tubular actuator having inner magnets, i.e., the coils enclose the permanent magnet array. Another topology of the tubular actuator having a Halbach magnet array is the one having outer magnets where the magnet array encloses the coils [14]. The results of these four topologies are presented in Table III.

The other parameters of the actuator, the pole pitch τ_p , and the magnet height, have a negligible effect on the actuator topology with the nonmagnetic core. The effect of these parameters on the

TABLE III
MINIMUM NUMBER OF SEGMENTS REQUIRED TO HAVE LESS THAN 1%, 3%,
AND 5% REDUCTION IN THE RADIAL COMPONENT OF THE FLUX DENSITY IN
THE AIR GAP, AS FUNCTION OF THE RATIO τ_{mr}/τ_p

<1% Reduction				
$\frac{\tau_{mr}}{\tau_p}$	non-magnetic core inner	outer	ferro-magnetic core inner	outer
0.3	7 - 8	8	9	9
0.4	8	9	9 - 10	9 - 10
0.5	9	10	10 - 11	10 - 11
0.6	9 - 10	10	10 - 11	10 - 11
0.7	10 - 11	11	11 - 12	11 - 12
<3% Reduction				
$\frac{\tau_{mr}}{\tau_p}$	non-magnetic core inner	outer	ferro-magnetic core inner	outer
0.3	4 - 5	5	5	5
0.5	6	6	6	6
0.7	6	7	7	7
<5% Reduction				
$\frac{\tau_{mr}}{\tau_p}$	non-magnetic core inner	outer	ferro-magnetic core inner	outer
0.3	4	4	4	4
0.5	4	5	5	5
0.7	5	5	5	5

topology with the ferro-magnetic core is very small, however, in general the following trend is observed:

- decreasing the pole pitch results in a reduced effect;
- increasing the magnet height results in a reduced effect.

Varying the air gap length does not affect the reduction of the magnetic field due to segmentation. The length of the air gap only affects the absolute value of the flux density in the center of the air gap, the effect of the segmentation is not affected.

B. Practical Implementation

Although this paper shows that approximating the radial magnetized ring magnet by a high number of segments results in the best approximation, during manufacturing the segments have to be glued together. Because a thin layer of glue and a coating on the magnet is present between all magnets, a high number of segments results in large number of glue layers. Especially in small actuators, this can significantly reduce the total amount of magnetic material present in the ring magnet which reduces the magnetic field in the air gap. On the other hand, using multiple segments for the radial ring magnet glued with nonconducting glue reduces the eddy current losses in the magnet array. Therefore, a tradeoff has to be investigated during the design of the actuator.

VI. CONCLUSION

Tubular actuators with Halbach magnetization are often approximated with segmented ring magnets to avoid a complex magnetization process. The ring magnets, ideally magnetized in

the radial direction, are approximated by diametrically magnetized segments. In this paper, a 3-D model describing the magnetic fields due to this segmented magnets is presented. To calculate the effective component of the flux density producing the force in the axial direction, a 2-D approximation of this 3-D model is derived. Using this model, the effect of the approximated ring magnets can be calculated. The effect of using a different number of segments on the different harmonics of the magnetic field is presented for three different actuator designs from literature. Additionally, a more elaborated analysis is performed to investigate the effect of the design parameters on the reduction of the magnetic field due to segmentation. The results are generalized and presented in a table that can be used to select the minimum number of segments required to have a small reduction in the magnetic field.

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