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轴向磁场电机永磁体空载涡流损耗减小方法对比研究

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Comparative Study on Methods for Reducing No-Load Eddy Current Losses of Permanent Magnets in Axial Magnetic Field Motors

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Abstract: The main methods to reduce the no-load eddy current loss of permanent magnets of axial magnetic field motors include: reducing the width of the stator slot opening, increasing the length of the air gap, dividing the permanent magnet into blocks, using shielding layers and magnetic slot wedges, etc. Based on a simplified 2D analysis model of a permanent magnet axial field motor, the effects of reducing stator slot opening width and increasing air gap length, using shielding layers and magnetic slot wedges to reduce no-load eddy current losses are analyzed. The effects of different segmentation methods of permanent magnets on reducing no-load eddy current losses are studied through three-dimensional electromagnetic field simulation. The research results indicate that reducing the width of the stator slot opening has the best effect; although increasing the length of the air gap can significantly reduce eddy current losses, the amount of permanent magnets used increases rapidly; the segmented permanent magnet has a better effect on reducing eddy currents, and the circumferential segmentation method is the best; the shielding layer has a counterproductive effect; the effect of using segmented magnetic slot wedges is slightly worse than reducing the width of stator slot openings, but the processing technology difficulty is lower.

Key words: axial magnetic field motors; eddy current losses; simplified 2D analysis model; magnet segmentation; shielding layer; magnetic slot wedge

摘 要:减少轴向磁场电机永磁体空载涡流损耗的方法主要有:减小定子槽开口宽度、增大气隙长度、永磁体分块、使用屏蔽层和磁性槽楔等。基于轴向磁场电机的简化二维分析模型,分析了减小定子槽开口宽度和增大气隙长度、使用屏蔽层和磁性槽楔降低空载涡流损耗的效果。通过三维电磁场仿真,研究了永磁体不同分块方式对减少空载涡流损耗的效果。研究结果表明,减小定子槽开口宽度的效果最佳;虽然增加气隙长度可以显著减小涡流损耗,但永磁体用量迅速增加;永磁体分块减小涡流效果较好,且周向分块方式最好;屏蔽层起反作用;使用分段磁性槽楔效果比减小定子槽开口宽度稍微差一点,但加工难度要低些。

关键词:轴向磁场电机;涡流损耗;简化二维分析模型;永磁体分块;屏蔽层;磁性槽楔

0 引言

轴向磁场永磁电机因其结构紧凑、电枢绕组散热条件良好、具有非常大的功率密度和转矩密度,在电动汽车驱动系统、航空发电系统等领域具有广泛的应用。

目前进入商业应用阶段的稀土永磁材料,通

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常电阻率都较低[1]。由于永磁体为实心结构,由定子齿槽效应引起的齿谐波磁场以及电枢电流引起的谐波磁场在转子永磁体上会感应出巨大的涡流,从而导致巨大的涡流损耗。很多学者对永磁电机永磁体的涡流损耗做过分析,如永磁同步电机涡流损耗解析计算模型[2-5]、利用屏蔽层和永磁体分段等方法来减小涡流损耗[6-8]以及轴向磁场永磁电机的涡流分析[9-13]等。

永磁电机永磁体空载涡流损耗减小方法主要有:减小定子槽开口宽度、增大气隙长度、永磁体分块、使用屏蔽层和磁性槽楔等。本文对轴向磁场永磁电机空载时永磁体涡流损耗的减小方法进行了对比分析:基于一种轴向磁场永磁电机的简化二维分析模型,分析了减小定子槽开口宽度和增大气隙长度、使用屏蔽层及磁性槽楔对减小空载涡流损耗的效果,并通过三维电磁场仿真研究了永磁体不同分段方式对减少空载涡流损耗的效果。

1　简化二维分析模型

对于非平行齿轴向磁场永磁电机,可以将其等效为一个直线电机,直线电机的厚度为永磁体沿半径方向的长度,如图 1 所示。电机的主要尺寸参数如表 1 所示。二维模型为在永磁体所在位置的平均半径处,将电机展开成的平面模型。

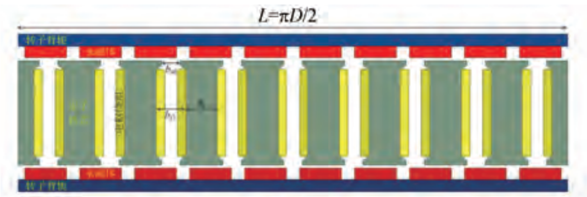


图 1　轴向磁场电机二维仿真模型

Fig. 1　Two-dimensional simulation model of axial magnetic field motor

三维模型和二维模型仿真得到的空载线反电势和电磁转矩对比如图 2 所示。需要注意的是,二维模型由于是直线电机模型,仿真得到的直接结果是电磁推力,与旋转电机模型对照时,需要将电磁推力的结果乘以平均半径 0.079 m,从而得到相对应的电磁转矩。线反电势二维仿真结果为 132 V,三维仿真结果为 135 V,两者相差 2.2%。电磁转矩二维仿真结果为 75 N·m,三维仿真结果为 77 N·m,两种相差 2.6%。误差原因可能在于,二维仿真未考虑端部效应。

表 1　轴向磁场永磁电机的尺寸参数

Tab. 1　Dimensional parameters of axial field permanent magnet motors

参数名称	参数值	参数名称	参数值
极对数	10	定子槽数	18
额定转矩/(N·m)	80	定子外径/mm	185
额定电流/A	160	定子内径/mm	131
定子铁心长度/mm	46	绕组每相总串联匝数	54
磁钢厚度/mm	5	定子槽开口宽度平均值/mm	8.6
额定转速/(r·min^{-1})	3 000	最高转速/(r·min^{-1})	6 000
峰值(启动)电流/A	500	转子外径/mm	185

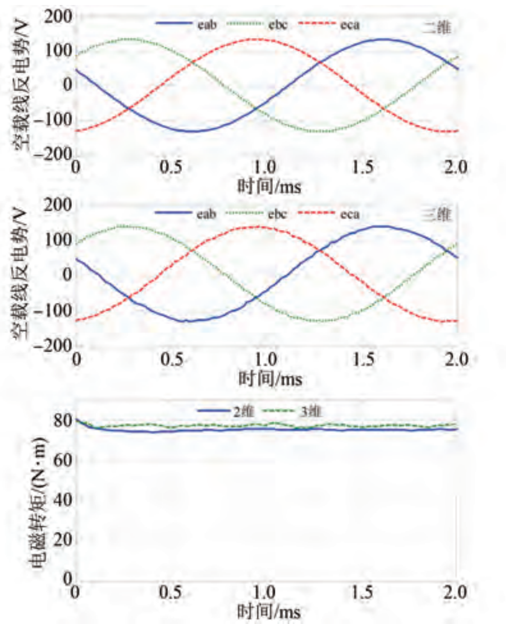


图 2　轴向磁场电机三维和二维空载线反电势和电磁转矩仿真结果

Fig. 2　Three-dimensional and two-dimensional no-load line back electromotive force and electromagnetic torque simulation results of axial magnetic field motor

2　涡流产生原因分析

空载时,气隙磁密可以表示为

$$B_\delta = F_m \cos(n_p\theta - \omega_m t)\sum_1^\infty [\Lambda_0 + \Lambda_k \cos(kZ_s\theta)] \tag{1}$$

式中:F_m 为永磁体磁动势基波幅值;n_p 为永磁体极对数;Λ_0 和 Λ_k 分别为气隙磁导的直流分量和

k 次分量；ω_m 为电角频率；t 为时间；Z_s 为定子槽数；θ 为空间角度。其中直流分量与磁动势作用产生的磁场为基波磁场，与转子同步旋转，不会在永磁体上产生涡流损耗。因此，只需考虑气隙磁场的谐波分量，磁导谐波含量与永磁体磁动势作用产生的磁场为

$$B_\delta = \frac{1}{2}\sum_{1}^{\infty} F_m \Lambda_k \cos(n_p\theta - \omega_m t \pm kZ_s\theta) \quad (2)$$

从式(2)可以看出，气隙谐波磁场的极对数为 $n_p \pm kZ_s$，主要考虑 $k=1$，2 的情形。当 $n_p=10$、$Z_s=18$ 时，谐波磁场极对数为 8、26、28 和 46，上述谐波磁场与永磁体转子之间存在相对运动。以永磁转子为参考坐标系，气隙谐波磁场的表达式为

$$B_\delta = \frac{1}{2}\sum_{1}^{\infty} F_m \Lambda_k \cos\left[(kZ_s \pm n_p)\theta + \frac{kZ_s}{n_p}\omega_m t\right] \quad (3)$$

从式(3)可以看出，谐波磁场与转子相对运动，在永磁体中产生涡流的频率是电源基波频率的 kZ_s/n_p 倍。电机空载时，气隙磁密波形及谐波含量仿真结果如图 3 所示，可以看出，谐波磁场极对数主要为 8、26、28、30 和 46。其中 30 对极的谐波磁场由磁动势谐波的 3 次分量和气隙磁导直流分量相互作用产生，与转子同步旋转，不会产生涡流。

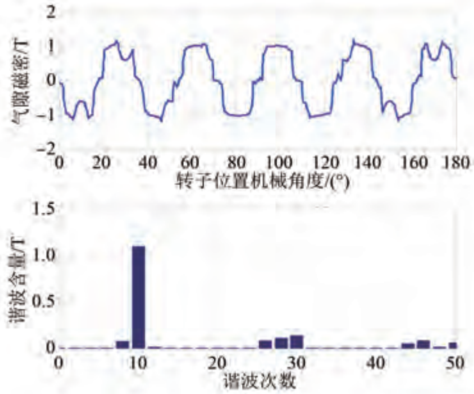


图 3 空载气隙磁密波形及谐波含量
Fig. 3 No-load air gap magnetic density waveform and harmonic content

3 减小涡流损耗的方法

3.1 减小定子槽开口宽度

已有许多文献[14-16]对定子齿谐波磁场进行了分析，研究结果表明：定子齿谐波磁场的幅值与定子槽开口宽度与气隙长度的比值有关，该比值越大，则齿谐波磁场的幅值越大。根据文献中的研究结果，永磁体的空载涡流损耗与齿谐波磁场幅值的平方和转速的 1.5 次方成正比[15-16]。有限元仿真得到的空载气隙磁密的谐波含量随定子槽开口宽度的变化曲线如图 4 所示。从图 4 可以看出，仿真结果与文献结果相吻合。

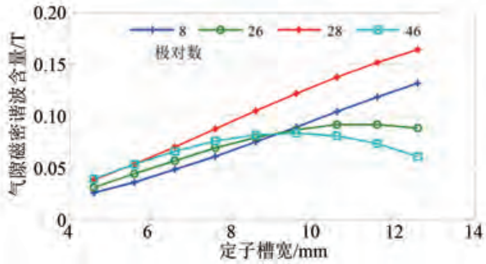


图 4 空载气隙磁密谐波含量随定子槽开口宽度的变化曲线
Fig. 4 The variation curves of no-load air gap magnetic density harmonic content with stator slot width

当转速为 3 000 rpm 时，由二维模型仿真得到的电机空载永磁体涡流损耗、绕组磁链和绕组自感与定子槽开口宽度之间的关系如图 5 所示。可以看出，定子槽开口宽度越小，则永磁体涡流损耗越小，绕组磁链幅值越大，但影响不大。另一方面，定子槽开口宽度的大小对电机定子槽漏感的大小影响非常大，定子槽开口宽度越小，则电机定子槽漏感越大。因此，在设计电机时，选取定子槽开口宽度应使得永磁体涡流损耗的大小下降到可接受的水平，且槽漏感的大小又不能太大。同时还给出了永磁体涡流损耗的三维磁场仿真结果，可以看出，二维和三维仿真结果相近，其误差原因可能为二维磁场仿真未考虑涡流在端部的影响。精度要求不是很高时，为了进行快速仿真分析，可以使用二维仿真模型来进行分析。

3.2 增大气隙长度

为了分析气隙长度对永磁体涡流损耗的影响，使用简化二维模型进行了仿真计算。仿真时，使永磁体的厚度和气隙长度的比值保持不变，从而可以使得电机气隙磁密基本保持不变。有限元仿真得到的空载气隙磁密的谐波含量和空载永磁体涡流损耗随气隙长度变化曲线如图 6 所示，可以看出，气隙长度越大，气隙磁密谐波含量越小，涡流损耗越小。但气隙长度越大意味着永磁体厚

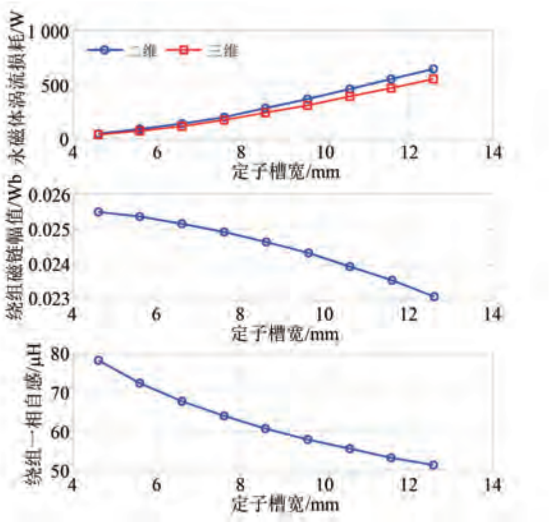


图 5　永磁体涡流损耗、绕组磁链和绕组自感与定子槽开口宽度的关系

Fig. 5　The relation between the eddy current loss of permanent magnet, the flux linkage and self-inductance of winding and the width of stator slot opening

度越大，使得电机的永磁体用量增加。因此，虽然可以使用增大气隙长度的方法来减小永磁体涡流损耗，但永磁体用量会迅速增加。仿真得到的空载永磁体涡流损耗与槽开口宽度和气隙长度之间的关系如图 7 所示。

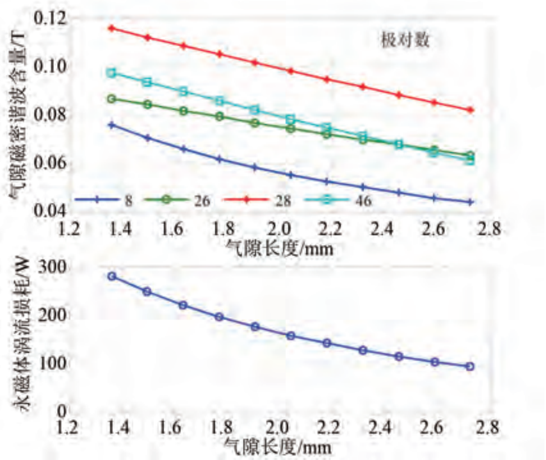


图 6　空载气隙磁密谐波含量和永磁体涡流损耗随气隙长度变化曲线

Fig. 6　The change curves of harmonic content and eddy current loss of no-load air-gap magnetic density with air-gap length

3.3　永磁体分块

为减少永磁体涡流损耗，可采用将永磁体进行分块的方式。采用径向分块、周向分块以及径向和周向混合三种分块方式。为研究不同分块数及分块方式对减少涡流效果的影响，采用三维有限元计算了轴向磁场电机空载时的永磁体涡流损耗。永磁体涡流损耗随径向或者周向分块数的变化曲线如图 8 所示。可以看出，分块数对涡流损耗影响非常大，分块数越多，有效涡流损耗减少得越多，涡流损耗与分块数近似成反比关系。还可以看出，周向分块减小永磁体涡流损耗的效果更好。当分块数为 4 时，采用三种不同分块方式对减少涡流损耗的效果对比如表格 2 所示，可以看出，周向分块方式效果最好，径向分块方式次之，而径向和周向混合分块方式效果最差。这是因为混合分块时，单块永磁体的径向和周向长度相对其它两种来讲要大，因此涡流更容易形成回路，涡流损耗更大。

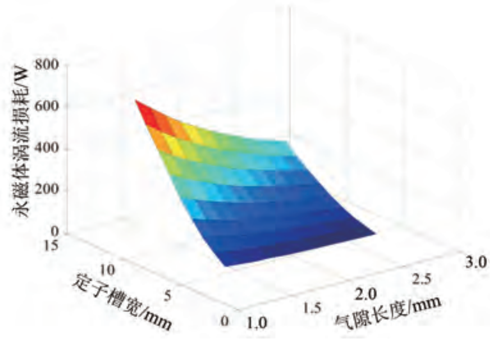


图 7　空载永磁体涡流损耗与槽开口宽度和气隙长度之间的关系

Fig. 7　The relation between eddy current loss of no-load permanent magnet and slot width and air gap length

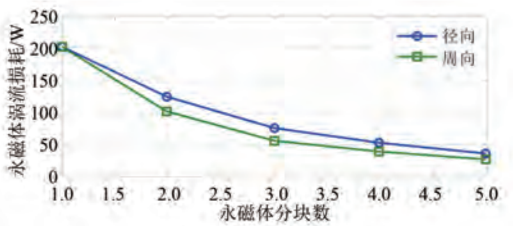


图 8　径向或者周向分块数对永磁体涡流损耗的影响

Fig. 8　Effect of radial or circumferential number of blocks on eddy current loss of permanent magnet

表 2　三种分块方式对比

Tab. 2　The comparison of three segmentation methods

	径向	周向	混合
永磁体涡流损耗/W	53	39	77

3.4 使用屏蔽层

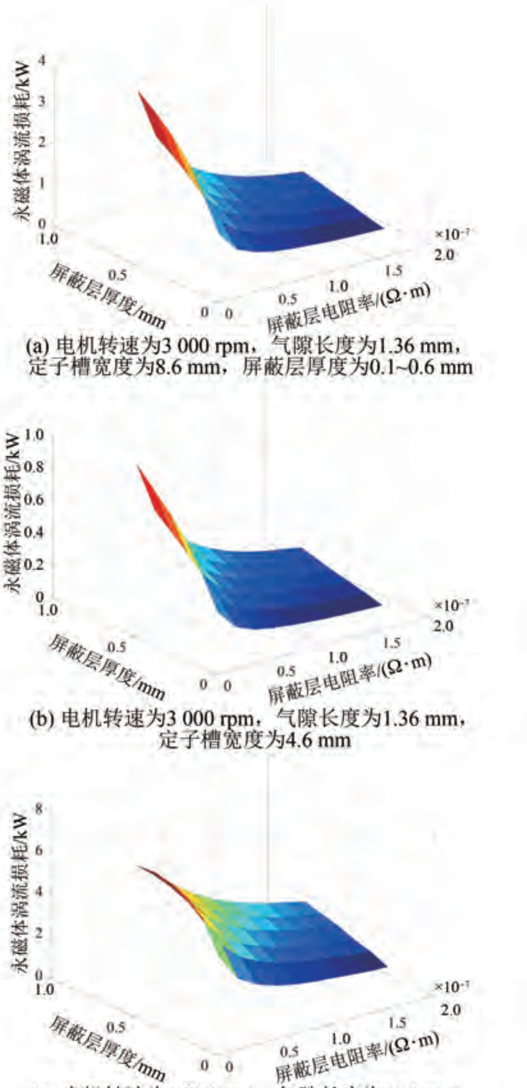
为了减小涡流损耗,通常可以在永磁体表面覆盖一层高导电率的金属材料,例如铜[17-21]。本文使用了简化二维模型,分析了铜屏蔽层参数对涡流损耗的影响。

当电机转速为 3 000 rpm、气隙长度为 1.36 mm、定子槽宽度为 8.6 mm、屏蔽层厚度为 0.1~0.6 mm 时,仿真得到的空载转子涡流总损耗与屏蔽层厚度和电阻率之间的关系如图 9(a)所示。可以看出,空载转子涡流总损耗随屏蔽层厚度增加而增加,随屏蔽层电阻率增加而减小,并且屏蔽层并不能使转子涡流总损耗降低。当电机转速为 3 000 rpm、气隙长度为 1.36 mm、定子槽宽度为 4.6 mm 时,空载转子涡流总损耗与屏蔽层厚度和电阻率之间的关系如图 9(b)所示。可以看出,定子槽宽度减小时,转子涡流损耗迅速减小,但转子涡流总损耗随屏蔽层厚度和电阻率变化规律不变。当电机转速为 6 000 rpm、气隙长度为 1.36 mm、定子槽宽度为 8.6 mm 时,空载转子涡流总损耗与屏蔽层厚度和电阻率之间的关系如图 9(c)所示。可以看出,空载转子涡流总损耗随屏蔽层厚度和电阻率的变化规律与上面基本相同,但当转速为 6 000 rpm 时,当屏蔽层厚度较大时,总损耗随着屏蔽层厚度增加的趋势变得缓慢。

本文的仿真结果与文献[17-21]不相符的原因在于,本文电机的转速不是很高,气隙谐波磁场与转子相对运动产生的涡流对应的电频率比文献[17-21]要低,因此对应铜材料的透入深度要大得多。由于屏蔽层厚度要比气隙长度小,通常,屏蔽层能取得的最大值比透入深度要小。所以本文的仿真结果与文献[22-23]中的结果相一致。

3.5 使用磁性槽楔

为了减小涡流损耗,可以采用磁性槽楔,如图 10 所示。空载时电机气隙磁密的谐波含量随槽楔厚度变化曲线如图 11 所示。可以看出,谐波含量随槽楔厚度的增加而减小,因此,永磁体涡流损耗随槽楔厚度的增加而减小。但磁性槽楔会导致电机绕阻的电感增加,同时,还会使得电机的漏磁增加,而主磁通减小。使用简化有限元模型仿真了磁性槽楔的厚度对永磁体涡流损耗、绕组磁链



(a) 电机转速为3 000 rpm, 气隙长度为1.36 mm, 定子槽宽度为8.6 mm, 屏蔽层厚度为0.1~0.6 mm

(b) 电机转速为3 000 rpm, 气隙长度为1.36 mm, 定子槽宽度为4.6 mm

(c) 电机转速为6 000 rpm, 气隙长度为1.36 mm, 定子槽宽度为8.6 mm

图 9 空载转子涡流总损耗与屏蔽层厚度和电阻率之间关系

Fig. 9 The relation between the total eddy current loss of the no-load rotor and the thickness and resistivity of the shield

及绕组电感的影响,仿真结果如图 12 所示。可以看出,磁性槽楔可以显著减小涡流损耗,但也会使得绕组磁链减小,绕组电感迅速增加;还可以看出,磁性槽楔厚度应小于 0.3 mm。此时,绕组磁链的减小值不是太大,绕组自感也不是太大,并且永磁体涡流损耗有较大幅度的减小。

当使用分段槽楔时,如图 10(b)所示,槽楔厚度取固定值为 2 mm,空载时气隙磁密的谐波含量随槽楔间隙宽度的变化曲线如图 13 所示。可以看出,气隙磁密的谐波含量随槽楔间隙宽度的增

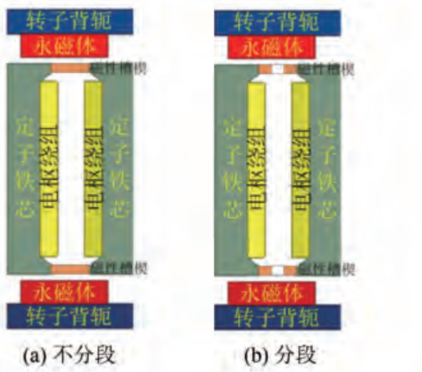


图 10　槽楔示意图：(a)不分段；(b)分段

Fig. 10　Groove wedge schematic diagram: (a) not segmented; (b) segmented

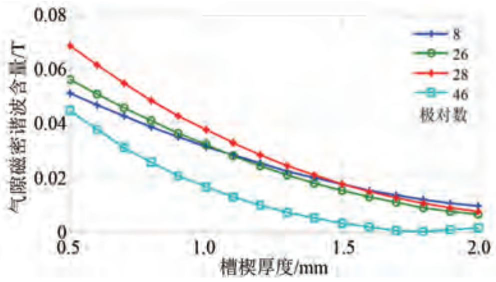


图 11　空载气隙磁密谐波含量随槽楔厚度变化曲线

Fig. 11　The variation curves of no-load air gap magnetic density harmonic content with slot wedge thickness

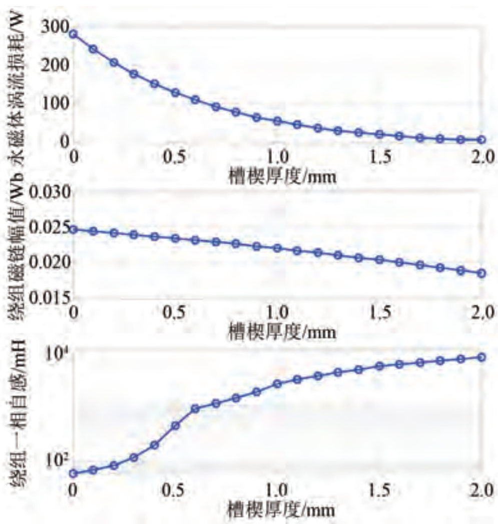


图 12　永磁体涡流损耗、绕组磁链幅值及绕组自感随磁性槽楔厚度的变化曲线

Fig. 12　The curves of eddy current loss of permanent magnet, amplitude of flux linkage and self-inductance of winding with the thickness of magnetic slot wedge

加而增加，与气隙磁密的谐波含量随定子槽开口宽度的变化规律相同。通过对比图 4 和图 13 还可以看出，图 4 和图 13 各次谐波含量的大小基本相同。永磁体涡流损耗、绕组磁链和绕组自感与槽楔间隙宽度的关系如图 14 所示，作为对比，还给出了永磁体涡流损耗、绕组磁链和绕组自感与定子槽开口宽度的关系图。通过对比可以看出，半闭口槽相比磁性槽楔，永磁体涡流损耗更低，绕组磁链幅值更高，绕组自感更低，但两者相差不大。同时对比图 12 和 14 可以看出，分段后，减小涡流损耗效果较好，并且绕组磁链幅值更大，绕组的自感更小。因此，应该采用分段槽楔。

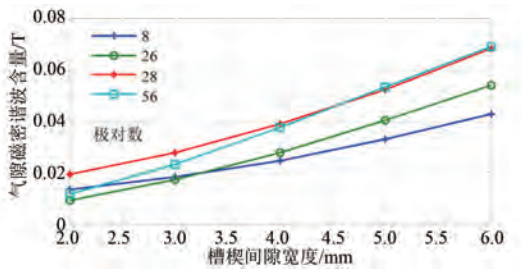


图 13　空载气隙磁密谐波含量随槽楔间隙宽度的变化曲线

Fig. 13　The change curves of no-load air gap magnetic density harmonic content with slot wedge gap width

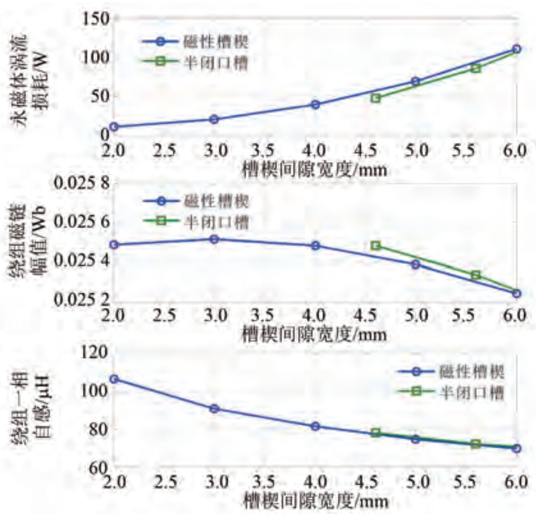


图 14　永磁体涡流损耗、绕组磁链和绕组自感与槽楔间隙宽度的关系

Fig. 14　The relation of eddy current loss of permanent magnet, flux linkage and self-inductance of winding and slot wedge gap width

空载永磁体涡流损耗与槽楔厚度和间隙宽度之间的关系如图 15 所示，绕组磁链与槽楔厚度和间隙宽度之间的关系如图 16 所示，绕组自感与槽

楔厚度和间隙宽度之间的关系如图 17 所示。可以看出，槽楔厚度越薄，槽楔间隙宽度越大，则空载永磁体涡流损耗越大。槽楔厚度越厚，槽楔间隙宽度越大，则绕组磁链越大。槽楔厚度越薄，槽楔间隙宽度越大则绕组的自感越小。

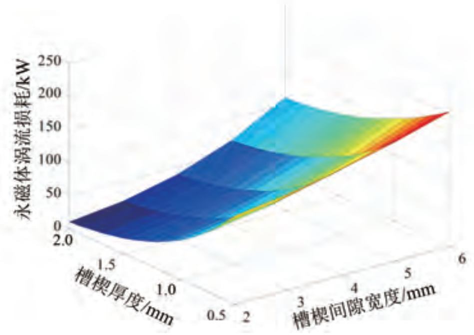


图 15　空载永磁体涡流损耗与槽楔厚度和间隙宽度之间的关系

Fig. 15　The relation between eddy current loss of no-load permanent magnet and wedge thickness and gap width

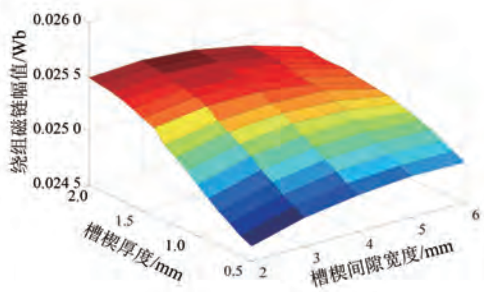


图 16　绕组磁链与槽楔厚度和间隙宽度之间的关系

Fig. 16　The relation between winding flux linkage and slot wedge thickness and gap width

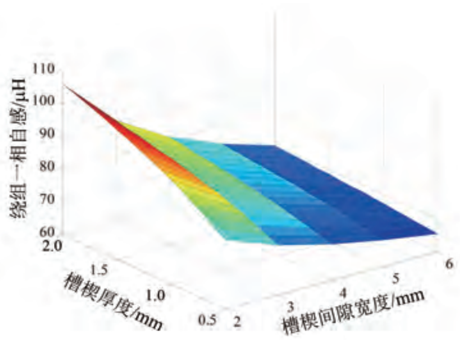


图 17　绕组自感与槽楔厚度和间隙宽度之间的关系

Fig. 17　The relation between winding self-inductance and slot wedge thickness and clearance width

槽楔不同分段数时，气隙磁场谐波含量随槽楔厚度的变化曲线如图 18 所示。可以看出，分段数越多，谐波含量越大。槽楔不同分段数时，永磁体涡流损耗、绕组磁链幅值及绕组自感随槽楔厚度的变化曲线如图 19 所示。可以看出，分段数越小，永磁体涡流损耗越低，绕组磁链越大，但绕组自感也越大。从减小涡流损耗角度出发，分段数应取 2。

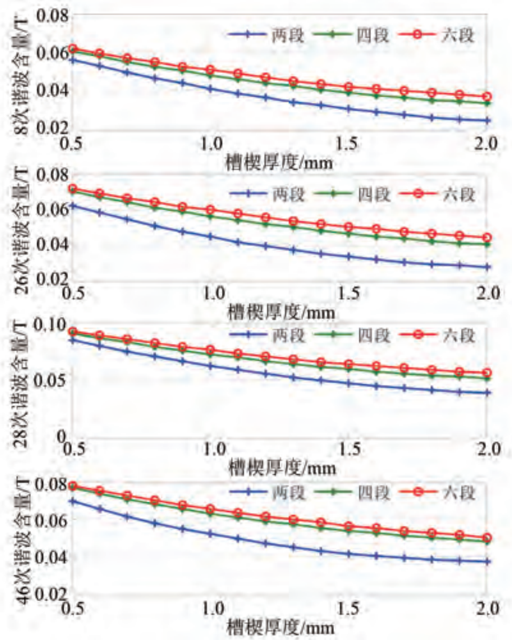


图 18　槽楔不同分段数时，气隙磁场谐波含量随槽楔厚度的变化曲线

Fig. 18　When the number of groove wedges is different, the change curves of the harmonic content of the air gap magnetic field with the thickness of slot wedges

各种涡流损耗减小方法的对比如表 3 所示。可以看出，减小定子槽开口宽度的效果最佳，但因为轴向磁场电机的定子铁心多采用冲卷工艺加工，槽开口宽度很小时，齿顶呈细条形，加工难度很大；增加气隙长度虽然可以显著减小涡流损耗，但永磁体用量迅速增加，不可取；永磁体分块减小涡流效果较好，且周向分段方式最好，但分块数多时，永磁体安装变得复杂；屏蔽层不能减小涡流损耗，反而起反作用；使用分段磁性槽楔效果比减小定子槽开口宽度方法的效果稍微差一点，但使用磁性槽楔时，由于磁性槽楔形状规则，易采用硅钢片叠压方式进行加工，然后再将磁性槽楔通过卡

表 3 各种涡流损耗减小方法的对比

Tab. 3 Comparison of various eddy current loss reduction methods

方法	优点	缺点
减小定子槽开口宽度	可以显著减小涡流损耗	绕组自感随定子槽口宽度减小而增大,槽开口宽度较小时加工工艺难度大
增加气隙长度	可以显著减小涡流损耗	永磁体用量增加
永磁体分块	减小涡流效果较好,且周向分块方式最好	分块数多时,永磁体安装复杂
使用屏蔽层	无	不能减小涡流损耗,反而起反作用
使用磁性槽楔	减小涡流损耗效果较好,加工工艺简单	绕组自感随槽楔间隙宽度减小而增大

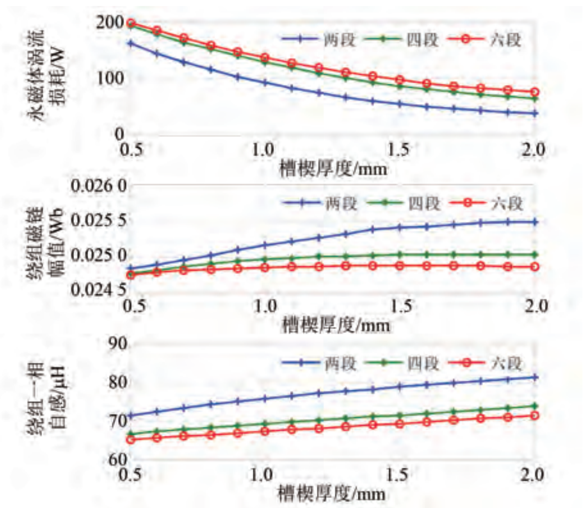


图 19 槽楔不同分段数时,永磁体涡流损耗、绕组磁链幅值及绕组自感随槽楔厚度的变化曲线

Fig. 19 When the number of slot wedges is different, the eddy current loss of permanent magnet, the amplitude of winding flux linkage and the winding self-inductance change curves with the thickness of slot wedges

槽方式固定在定子上,相对来讲难度要低些,最值得推荐。

4 结语

本文对轴向磁场永磁电机空载时永磁体涡流损耗的减小方法进行了对比分析。基于一种轴向磁场永磁电机的简化二维分析模型,分析了减小定子槽开口宽度和增大气隙长度、使用屏蔽层及磁性槽楔对减小空载涡流损耗的效果,并通过三维电磁场仿真研究了永磁体不同分块方式对减少空载涡流损耗的效果。研究结果表明:减小定子槽开口宽度的效果最佳,但加工工艺难度大;增大气隙长度虽然可以显著减小涡流损耗,但永磁体用量迅速增加;永磁体分块减小涡流效果较好,且周向分块方式最好,但分块数多时,永磁体安装变得复杂;屏蔽层不能减小涡流损耗,反而起反作用;使用分段磁性槽楔效果比减小定子槽开口宽度稍微差一点,且分段数应取 2,但加工难度要低些,最值得推荐使用。

参 考 文 献

[1] 黄光伟, 陆通, 王亚娜, 等. 高电阻率钕铁硼永磁材料的研究进展与展望[J/OL]. 中国稀土学报, 2023-1-20. https://link.cnki.net/urlid/11.2365.TG.20230424.1441.002.
HUANG G W, LU T, WANG Y N, et. al. Research progress and prospect of high electrical resistivity Nd-Fe-B permanent magnetic materials [J/OL]. Journal of the Chinese Society of Rare Earths, 2023-1-20. https://link.cnki.net/urlid/11.2365.TG.20230424.1441.002.

[2] 郭伟林, 彭利明, 张芳. 高速永磁同步电机转子涡流损耗分析[J]. 微电机, 2022, 55(11): 36-41.
GUO W L, PENG L M, ZHANG F. Analysis of rotor eddy-current loss in high-speed permanent magnet synchronous motors [J]. Micromotors, 2022, 55(11): 36-41.

[3] 李剑, 江晓波, 孙鲁. 考虑定子饱和的航空高速永磁电机转子涡流损耗解析模型[J]. 微电机, 2022, 55(1): 12-16+24.
LI J, JIANG X B, SUN L. An analytical model of rotor eddy current loss in aero high speed permanent magnet motor considering stator saturation [J]. Micromotors, 2022, 55(1): 12-16+24.

[4] 佟文明, 潘雪龙, 高俊, 等. 多层护套结构高速永磁电机转子机械强度与损耗分析[J]. 电机与控制学报, 2022, 26(8): 21-29.
TONG W M, PAN X L, GAO J, et al. Analysis of mechanical strength and loss of high-speed permanent magnet motor rotor with multi-layer sleeves structure [J]. Electric Machines and Control, 2022, 26(8):

21-29.

[5] 佟文明, 田野, 李晓健, 等. 双层复合护套高速永磁电机转子涡流损耗解析模型[J/OL]. 电工技术学报, 2023-1-13. https://doi.org/10.19595/j.cnki.1000-6753.tces.230844.
TONG W M, TIAN Y, LI X J, et al. Analytical modeling for rotor eddy current loss of high-speed surface-mounted permanent magnet motor with double-layer compound retaining sleeve [J/OL]. Transactions of China Electrotechnical Society, 2023-1-13. https://doi.org/10.19595/j.cnki.1000-6753.tces.230844.

[6] 李子钊, 王书华, 汪旭东, 等. 高速永磁同步电动机转子涡流损耗优化[J]. 上海电机学院学报, 2023, 26(3): 153-158.
LI Z Z, WANG S H, WANG X D, et al. Optimization for the rotor eddy current loss in high-speed permanent magnet synchronous motor [J]. Journal of Shanghai Dianji University, 2023, 26(3): 153-158.

[7] 刘柯, 周羽, 杨小宝, 等. 高速永磁同步电机结构对转子涡流损耗影响[J]. 微特电机, 2022, 50(12): 16-20+26.
LIU K, ZHOU Y, YANG X B, et al. Influence of the structure of high-speed permanent magnet synchronous motor on eddy current loss of rotor [J]. Small & Special Electrical Machines, 2022, 50(12): 16-20+26.

[8] 李伟, 江晓波, 孙鲁, 等. 带有不同屏蔽层结构的高速永磁电机转子涡流损耗分析与实验验证[J]. 现代机械, 2022, 3: 39-43+57.
LI W, JIANG X B, SUN L, et al. Analysis and experimental verification of rotor eddy current in high-speed PMSM with different shielding structures [J]. Modern Machinery, 2022, 3: 39-43+57.

[9] 刘福贵, 王振, 赵志刚. 定子无铁心轴向磁场永磁电机永磁体损耗研究[J]. 微电机, 2016, 49(4): 1-5+31.
LIU F G, WANG Z, ZHAO Z G. Analysis of permanent magnets eddy-current loss in stator coreless axial flux permanent motors [J]. Micromotors, 2016, 49(4): 1-5+31.

[10] 刘福贵, 杨乾坤, 王彦刚. 定子无铁心轴向磁场永磁电机永磁体涡流损耗研究[J]. 微特电机, 2017, 45(6): 12-16.
LIU F G, YANG Q K, WANG Y G. Study on eddy current loss of permanent magnet of ironless stator axial field permanent motor [J]. Small & Special Electrical Machines, 2017, 45(6): 12-16.

[11] 李雪, 刘福贵, 李宾, 等. 轴向磁场永磁同步电机转子涡流损耗研究[J]. 电机与控制应用, 2018, 45(6): 68-71+101.
LI X, LIU F G, LI B, et al. Research on rotor eddy current loss of axial magnetic field permanent magnet synchronous motor [J]. Electric Machines & Control Application, 2018, 45(6): 68-71+101.

[12] 李雪, 刘福贵, 李博, 等. 轴向磁场无铁心永磁电机的永磁体结构优化及其涡流损耗削弱[J]. 河北工业大学学报, 2019, 48(2): 33-40.
LI X, LIU F G, LI B, et al. Optimization of permanent magnet structure and weakening of eddy current loss in axial magnetic field coreless permanent magnet motor [J]. Journal of Hebei University of Technology, 2019, 48(2): 33-40.

[13] 朱峻玉. 驱制动一体化轮毂电机多物理场分析及损耗抑制研究[D]. 烟台: 烟台大学, 2023.
ZHU J Y. Multiphysical field analysis and research on loss suppression of in-wheel motor for driving and braking [D]. Yantai: Yantai University, 2023.

[14] FREEMAN E M. The calculation of harmonics, due to slotting, in the flux-density waveforms dynamo-electric machine [J]. Proceedings of the IEE-Part C: Monographs, 1962, 109(16): 581-588.

[15] STOLL R L, HANSON D J. Modeling tooth-ripple losses in the solid pole faces of synchronous machines using reversible permeability [C] // International Conferences on the Electrical Machines & Drives, Oxford, 1993.

[16] DRUBEL O, STOLL R L. Tooth ripple losses in salient pole synchronous machines [C] // International Conferences on the Electrical Machines & Drives, Seattle, 1999.

[17] SHAH M R, LEE S B. Rapid analytical optimization of eddy-current shield thickness for associated loss minimization in electrical machines [J]. IEEE Transactions on Industry Applications, 2006, 42(3): 642-649.

[18] SHAH M R, LEE S B. Optimization of shield thickness of finite-length solid rotors for eddy-current loss minimization [J]. IEEE Transactions on Industry Applications, 2009, 45(6): 1947-1953.

[19] SHAH M R, EL-REFAIE A M. Eddy-Current loss

minimization in conducting sleeves of surface PM machine rotors with fractional-slot concentrated armature windings by optimal axial segmentation and copper cladding [J]. IEEE Transactions on Industry Applications, 2009, 45(2): 720-728.

[20] LI W, QIU H, ZHANG X, et al. Influence of copper plating on electromagnetic and temperature fields in a high-speed permanent-magnet generator [J]. IEEE Transactions on Magnetics, 2012, 48 (8): 2247-2253.

[21] ZHOU F, SHEN J, FEI W, et al. Study of retaining sleeve and conductive shield and their influence on rotor loss in high-speed PM BLDC motors [J]. IEEE Transactions on Magnetics, 2006, 42 (10): 3398-3400.

[22] YU K X, LIU L J, XIE X F. Design consideration of eddy current losses for rotor of HIA with rectifier and capacitive loads [J]. IEEE Transactions on Plasma Science, 2018, 46(8): 2949-2953.

[23] 刘龙建. 基于感应子储能脉冲发电机的电容器重频充电系统瞬态分析及损耗研究[D]. 武汉: 华中科技大学, 2019.

LIU L J. Transient analysis of a repetitive frequency capacitor charging power system based on energy-storage pulsed homopolar inductor alternator and research on the losses [D]. Wuhan: Huazhong University of Science and Technology, 2019.

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Comparative Study on Methods for Reducing No-Load Eddy Current Losses of Permanent Magnets in Axial Magnetic Field Motors

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Key words: axial magnetic field motors; eddy current losses; simplified 2D analysis model; magnet segmentation; shielding layer; magnetic slot wedge

Permanent magnet axial magnetic field motors have the advantages of high power density and torque density, and have important applications in medium to high speed drives such as electric vehicles and aviation fields. The main methods to reduce the no-load eddy current loss of permanent magnets include: reducing the width of the stator slot opening, increasing the length of the air gap, dividing the permanent magnet into blocks, using shielding layers and magnetic slot wedges, etc.

The methods are compared and analyzed in this article for reducing eddy current losses in permanent magnet axial field motors. Based on a simplified 2D analysis model of a permanent magnet axial field motor, the effects of reducing stator slot opening width and increasing air gap length, using shielding layers and magnetic slot wedges to reduce no-load eddy current losses are analyzed. The effects of different segmentation methods of permanent magnets on reducing no-load eddy current losses are studied through three-dimensional electromagnetic field simulation.

As shown in Tab.1, the research results indicate that reducing the width of the stator slot opening has the best effect; although increasing the length of the air gap can significantly reduce eddy current losses, the amount of permanent magnets used increases rapidly; the segmented permanent magnet has a better effect on reducing eddy currents, and the circumferential segmentation method is the best; the shielding layer cannot reduce eddy current losses, but instead has a counterproductive effect; the effect of using segmented magnetic slot wedges is slightly worse than reducing the width of stator slot openings, but the processing technology difficulty is lower.

Tab. 1 Comparison of various eddy current loss reduction methods

Methods	Reduce the width of stator slot opening	Increase air gap length	Divide the permanent magnet into blocks	Use the shielding layer	Use magnetic slot wedges
Advantages	The eddy current loss can be reduced significantly	The eddy current loss can be reduced significantly	The effect of reducing eddy current is better, and circumferential subsection is the best	None	The effect of reducing eddy current loss is good, and the processing technology is simple
Disadvantages	The winding self-inductance increases with the decrease of stator slot width, and the machining process is difficult when the slot width is small	The amount of permanent magnet increases	When the number of blocks is large, the installation of permanent magnet is complex	Cannot reduce the eddy current loss	The winding self-inductance increases with the decrease of slot wedge gap width