Publication P1

J. Kolehmainen. 2006. Finite element analysis of two PM-motors with buried magnets. In: Sławomir Wiak, Maria Dems, and Krzysztof Komęza (editors). Recent Developments of Electrical Drives. Best Papers from the 16th International Conference on Electrical Machines (ICEM 2004). Cracow, Poland. 5-8 September 2004. Dordrecht, The Netherlands. Springer. Pages 51-58. ISBN 1-4020-4534-4.

Finite Element Analysis of two PM-Motors with Buried Magnets

J. Kolehmainen

ABB Oy, Electrical Machines, P.O.Box, FI-65101 Vaasa, Finland,
Phone: +358 (0) 50 33 41479, fax: +358 (0) 33 41065
e-mail: Jere.Kolehmainen@fi.abb.com

Abstract — **In this paper a permanent magnet synchronous motor (PMSM) with buried V-shape magnets is compared to a motor with unusual design with buried U-shape magnets in every second pole. It is shown that the motor design with U-shape magnets has same electrical properties than the design with V-shape magnets.**

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) with buried magnets have been considered in a wide range of variable speed drives. A buried magnet design has many advantages compared to designs with surface mounted and inset magnets. Flux concentration can be achieved which induces higher air gap flux density. Higher air gap flux density give a possibility to raise torque of a machine. The buried magnets construction also gives a possibility to form air gap and get smoother torque [1]. The rotor can also be produced easier. Some of the different rotor with buries magnets types are presented in Fig.1.

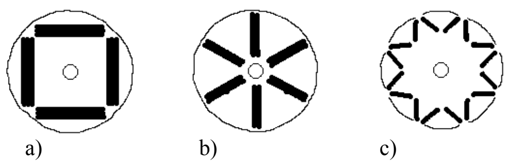

Figure 1. Rotor constructions of buried permanent magnet motors with a) tangential magnets b) radial magnets c) V-shape magnets

Buried magnet designs give the possibility to reduce reluctance by narrowing and lengthening the magnets but keeping the amount of the magnets the same. By using buried magnets in V-shape or radial magnets there are limits to reducing reluctance. Designs with U-shape magnets in every pole have good properties of both designs with V-shape and radial magnets [2]. However, with a design with U-shape magnets in every second pole it is possible to reduce reluctance further.

In this paper two buried magnet machines are compared, one with V-shape magnets and another with U-shape magnets in every second pole. The analysis is done by using time stepping and static calculations with Finite Element Method (FEM) [3]. Also these machines with different magnetic width and length are considered.

II. MOTOR DESIGNS

Both designs with buried magnets inside the rotor make the assembly of the rotor easier compared to the other designs. Rotor disks keep the magnets in place and no extra reinforcing bandage is needed. The magnets are inserted into punched slots in the laminated rotor iron. The example of design with buried magnets in V-shape is shown in Fig.2 and with buried U-shape magnets in every second pole in Fig.3.

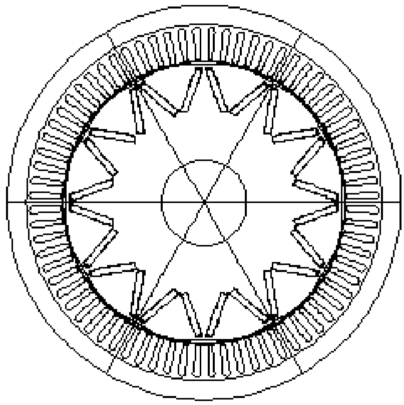

Figure 2. 12-pole PM motor design with magnets in V-shape.

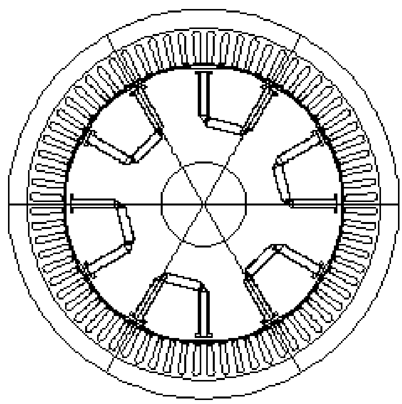

Figure 3. 12-pole PM motor design with magnets in U-shape in every second pole

The only difference of these two motors is in their internal rotor structure. Areas of the magnets are same and in the structure of Fig.3 magnets per one pole are thinner and longer. Also, a structure where magnets per one pole have same width and length is considered. In addition, all sizes of the iron bridges between the magnets and air gap are the same.

The number of magnet pieces in U-shape design is also reduced to ¾ of number in V-shape design. This saves time for inserting magnets to rotor.

III. CALCULATION RESULTS

The electrical properties of the motors with V-shape and the U-shape designs are studied. Studied motor data is shown in Table 1. Calculations are done with the time stepping method with FEM [3]. Properties are studied with different loads.

Table I Motor Data

Shaft height	280 mm
Power	27.5 kW
Voltage	370 V
Current	45 A
Pole number	12
Speed	300 rpm

In calculations voltage source and delta connection is used. Because of the different structure of rotors, two poles of each construction are modeled. Circuit of calculations is shown in Fig. 3. In the circuit there are three voltage sources, six winding connection and three end winding resistances and three end winding inductances. In all time stepping calculations, voltage angle of the stator and amplitude are same. Calculations are started with different rotor angles and stopped when transient phenomena is over. Constant rotor speed is used.

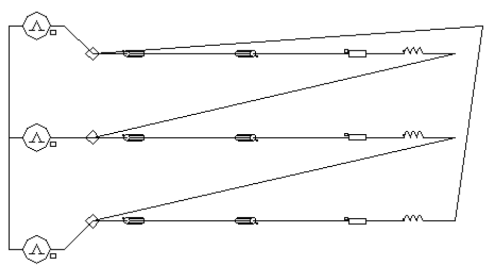

Figure 4. Circuit used in calculations.

The flux lines of three example designs with nominal load are shown in Figs 5, 6 and 7. The packing of the flux can also be seen. Every second pole in the U-shape designs is different which means that the structure between two poles is not symmetric. In Figs 5 and 6, total length, width and area of magnets per one rotor pole are same.

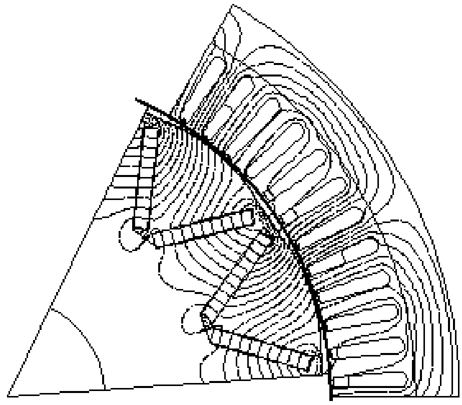

Figure 5. Packing of flux with nominal load and original design. (V-shape)

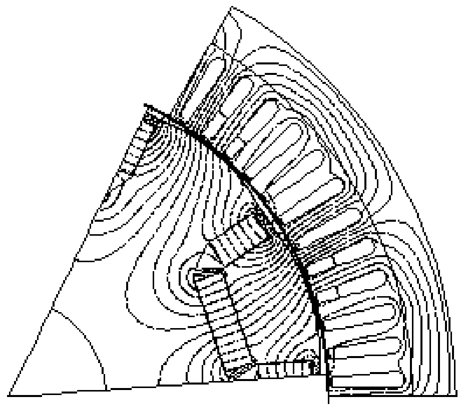

Figure 6. Packing of flux with nominal load and new design A. (U-shapeA)

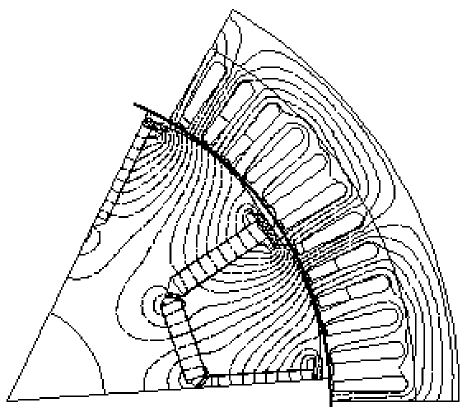

Figure 7. Packing of flux with nominal load and new design B. (U-shapeB)

Fig. 8 shows flux densities in the stator teeth as a function of time with nominal load calculations of V-shape and U-shapeA designs. The effect of difference of designs can be seen. It is relatively small. It can also be seen that absolute value of flux is periodically symmetric between two poles in our U-shapeA design. Flux is also symmetric with U-shapeB design. No deviation of symmetry can be seen.

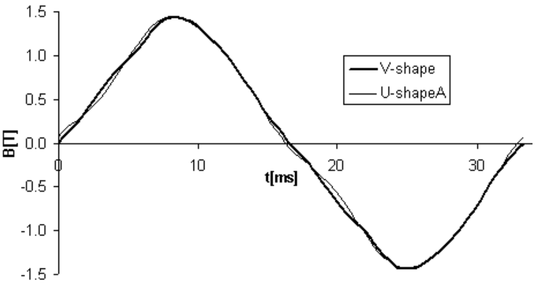

Figure 8. Flux densities of V-shape and U-shapeA designs in the stator teeth on one period with nominal loads.

Fig. 9 shows flux densities of V-shape and U-shapeA designs produced only by magnets in the stator teeth with different rotor angles. Length and width of magnets per one rotor pole are same. Maximum and average flux densities of V-shape and U-shapeA designs are 1.463 T, 1.420 T and 0.932 T, 0.926 T. Flux densities with U-shapeA design is slightly smaller because of small effect of gaps between the magnets.

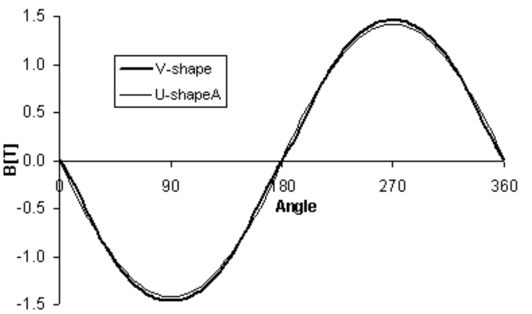

Figure 9. Flux densities of V-shape and U-shapeA designs produced only by magnets in the stator teeth with different rotor angles.

Nominal and maximum loads of our three example designs are calculated with time stepping calculations. In Table 2, the calculation results are compared to experimental results of V-shape design. It can be seen that calculation of V-shape design gives a correct current. Only copper losses in stator winding are taken accound in effiency η calculations. Other losses are relatively small.

In the table first calculated U-shapeA results are calculated with the design with same total magnet length and thickness per pole than with V-shape design. The second calculated results U-shapeB are calculated with design with longer and thinner magnets per pole. Magnets thickness, width and area are also shown in the table with unit of mm. Dimensions of V-shape design are real dimensions of one magnet and for U-shape designs dimension are values which corresponds values of V-shape design.

Table II Comparison of nominal load results

	Measured V-shape	Calculated V-shape	Calculated U-shapeA	Calculated U-shapeB
T_n[Nm]	875	875	875	875
I_n[A]	46.5	45.5	45.8	45.4
Cosφ	0.993	0.997	0.997	1.000
η	0.929	0.946	0.939	0.938
Angle		32.6	29.7	25.4
T_k[Nm]		1688	1557	1418
I_k[A]		122.5	113.8	98.5
Cosφ		0.856	0.841	0.804
Angle		114.1	111.5	99.2
Magnets	thickness	7.3	7.3	5.15
Magnets	width	52	52	72.2
Magnets	area	379.6	379.6	371.83

The maximum output torque with the first U-shapeA design is smaller than with the V-shape design and it has also smaller load angle difference. This is due to smaller reluctance torque and effect of iron bridges between the magnets. Torque and reluctance torque curves are shown in Fig. 10. Reluctance torque is larger with V-shape than with U-shapeA design, because the magnetic structure of rotor. By comparing torques of U-shapeA and U-shapeB designs can also see the effect of decreasing of magnet thickness. Reluctance and maximum torque is smaller with thicker magnets.

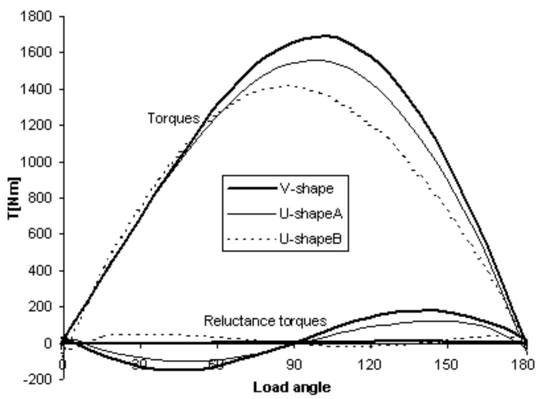

Figure 10. Torque and reluctance torque of motors with V- and U- shape designs as a function of load angle.

Power factors of V-shape and U-shape designs are shown as a function of torque in Figure 11. Power factor of the motor with the U-shapeA design is larger up to the nominal point and with the higher torque it is smaller. Nominal torque of the motors is 875 Nm and usually the motors are used with partial loads with different speeds. Hence, the motor with the U-shape magnets is usually in the torque range with better power factor. Also the maximum torque decreases because of the smaller reluctance. With the longer and thinner magnets in the V-shapeB design there is smaller maximum torque and higher power factor with nominal load as can be expected.

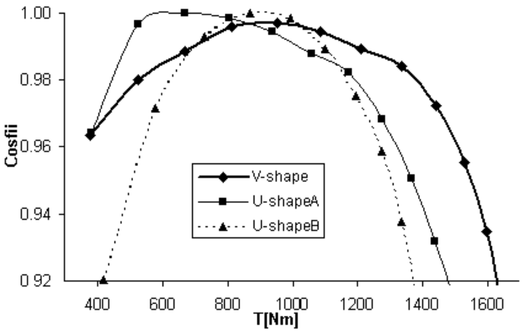

Figure 11. Power factor as a function of torque.

There is significant difference of torques between V- and U-shapeA designs. This is shown in the Figure 12. With the U-shapeA design, the oscillation of torque is with the frequency of magnets going over stator phase. With the V-shape design oscillation frequency is two times of frequency with U-shapes, because two magnets go over one stator phase with V-shape design while one magnet going over one stator phase with U-shapeA design. In addition the amplitude is smaller with V-shapes.

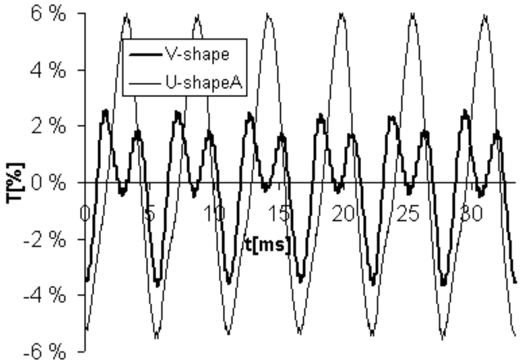

Figure 12. Torque oscillations of V-shape and U-shapeA designs.

IV. CONCLUSION

It is shown that the PM motor with the U-shape magnets in every second pole works as well as the conventional PM motor with the V-shape magnets in every pole. Asymmetrical structure of pole pairs in this design cause no asymmetry to the magnetic field of air gap. This design gives a possibility to get higher flux densities with the same amount of magnets. The number of magnet pieces is also reduced.

Torque oscillation with U-shapeA design is too high compared to V-shape design. This could be avoided with using different stator slots or iron structure near the magnets and air gap.

In conclusion, this new solution gives more possibilities to produce buried permanent motors with better power factor and efficiency.

REFERENCES

[1] Salo J., Heikkilä T., Pyrhönen J., Haring T., “New Low-Speed High-Torque Permanent Magnet Synchronous Machine With Buried Magnets”, *International Conference Electrical Machines (ICEM 00)*, vol. 3/3, pp. 1246-1250, 28- 30 August 2000, Espoo, Finland.

[2] Libert F., Soulard J., Engström J., “Design of a 4-pole Line Start Permanent Magnet Synchronous Motor”, *International Conference Electrical Machines (ICEM 02)*, pp. 173, 25- 28 August 1998, Brugge, Belgium.

[3] Flux2D software – www.cedrat.com