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Permanent Magnets Synchronous Machine with Rotor Poles Supported by Magnets

Jere Kolehmainen

Abstract— **A rotor of a buried permanent magnet machine can be constructed reliably by using magnets to support the rotor structure against centrifugal forces. In this work, a rotor solution with V- shape magnets in every pole are replaced with a rotor solution where every second pole are geometrically supported by the rest of the poles with the magnets. Effect of the replacement of the rotor is compared by simulating and by testing manufactured prototypes. Simulations are performed with electromagnetic and mechanical finite element methods. Obtained results show superiority of geometrically supported solution.**

Index Terms— **Electromagnetic analysis, permanent magnet machines, synchronous machines, variable speed drives.**

I. Introduction

PERMANENT magnet machines are come one of the most important applications for variable speed drives due to development of modern frequency converters with intelligent drive systems [1]. In many applications, also high rotational speeds are needed. High rotational speeds can be produced either with a conventional machine and a gearing system or with a high rotational speed machine without any gearing system [2-4]. Direct drive systems without gearing system are smaller and more effective. Modern frequency converter technology is also increased usability of direct drive systems with high rotational speeds. In addition, due to the growing awareness of environmental problems, better electric power efficiency is sought.

Surface and buried magnets in the rotors of permanent magnet synchronous machines are commonly used for high speed applications [2-4]. However, a high rotational speed machine needs some compromises between electrical and structural properties in the design.

High speed surface magnet solutions need often extra support against centrifugal forces. For example, supporting bandage [2] and form blocking [3] solutions are introduced. However, electrically similar machine could be produced also with the buried magnets and the thin bridges around the magnets, where the bridges retain the magnets still [4]. For increasing the strength of a buried magnet solution, some extra supporting devices, for example H- or I-bars or iron bridges are commonly used [5]. Particularly, the machine with the buried magnets with the V-shaped rotor poles is economically and electrically good solution.

The rotors with the buried V-shaped magnets are easy to produce by punching solid electric rotor sheets, assembling them together, and inserting the magnets. However, this structure needs some supporting devices. In the case of solid rotor sheets, some iron bridges are left to the structure in the punching process. Unfortunately, the supporting bridges decrease electrical properties, because the bridges are working as paths of the leakage flux [6]. In addition to use extra supporting devices mentioned earlier, it is also possible to replace great part of the supporting iron bridges with the structural support with a dovetail form of the poles [7-12].

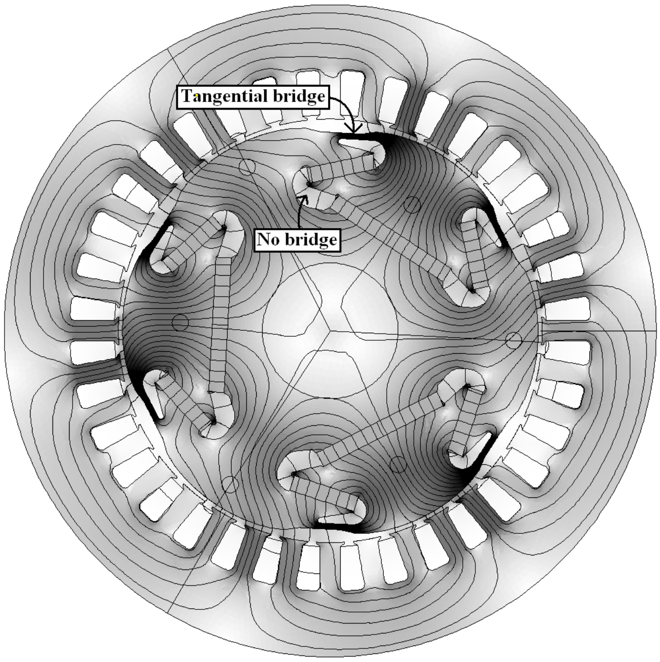

Fig. 1. Dovetail rotor design with flux density and lines. Possible places for supporting bridges are marked as “Tangential bridge” and “No bridge”.

The dovetail design, considered in this paper, is shown in Fig 1. The sorter magnets mainly support the rotor structure against centrifugal forces. The bridges between the poles also support the structure. This structure has only tangential bridges between the poles near the air gap, while the one earlier solution [7, 8] has no iron bridges between the poles and the other earlier solution has also iron bridges inside the rotor [9]. Places of the possible bridges, which corresponds the earlier solution [9], are marked with “Tangential bridges” and “No bridges” in Fig 1.

In this work, the dovetail solution is also compared to a traditionally used solution with the V-shaped poles. Comparisons are first done using electromagnetic and strength calculations using the finite element method (FEM) [13, 14]. Then, motors with the both rotor designs are manufactured and tested. Finally, the test results are compared together and against the calculations. The motor with the dovetail pole design is shown to be electrically and mechanically better choice to its application.

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Jere Kolehmainen is with ABB Oy, Motors, Vaasa, Finland (e-mail: jere.kolehmainen@fi.abb.com).

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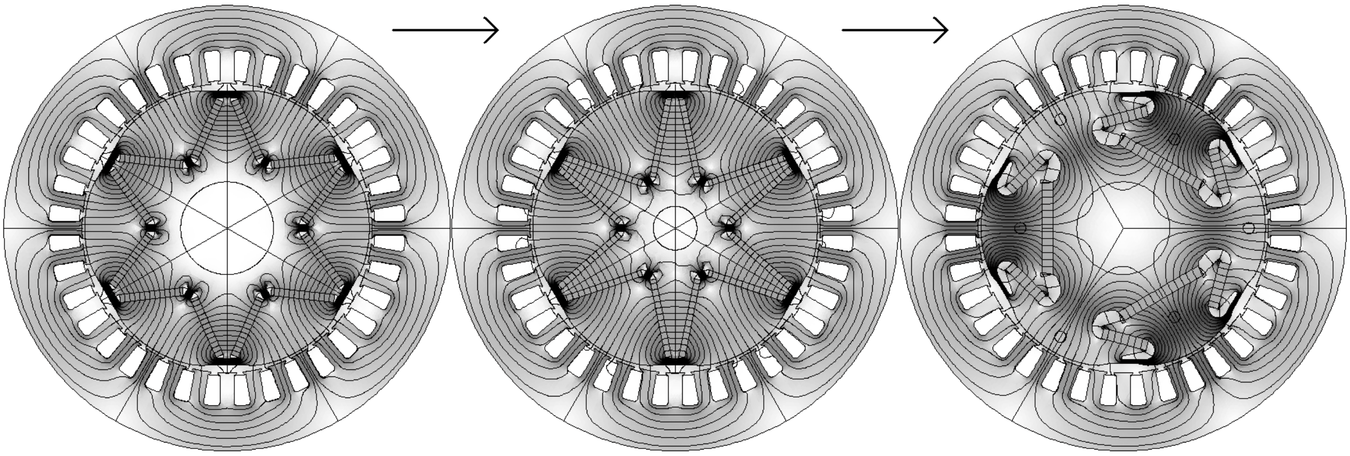

Fig. 2. Evolution of machine structure from V-shape rotor to dovetail rotor with flux density and lines.

TABLE I
NOMINAL VALUES AND MAIN DIMENSIONS OF STUDIED MACHINES

Quantity	Value
Shaft height (mm)	160
Power (kW)	45
Torque (Nm)	71.6
Voltage (V)	360
Current (A)	100
Speed (rpm)	6000
Stator outer diameter (mm)	254
Stator inner diameter (mm)	165
Stack length (mm)	165
Minimum air gap (mm)	1.5
Number of poles	6
Number of slots per pole per phase	2
Connection	Delta
Number of effective conductors in slot	8
Number of parallel branches	1

II. MACHINE DESIGN

A 6-pole motor with the V-shaped rotor poles is used as an example for comparison for the dovetail-shaped motor design. The only difference between the two motors is in their rotor structure. However, the amount of the magnetic material is kept same. The same air gaps between the magnets and the electric steel are also used. The rotor structures are shown in Fig. 2. The V-shape rotor has 6 symmetry sections, but the dovetail rotor has the magnets in every second pole and has then 3 symmetry sections. The dovetail rotor consists of three magnets in the every second pole (while the V-pole design has two magnets in the every pole) and the wedge-like pole shoe, which narrows towards the air gap. As the centrifugal force pushes the pole shoe outwards, the smaller magnets lock the pole firmly in place and prevent it from moving.

Although, modern permanent magnets materials are rather brittle, the magnets tolerate compressive stress surprisingly well (up to 800 MPa). At the same time, the large contact area between the pole wedge and the magnets renders the compressive stress to an acceptable level.

For manufacturing reason, the dovetail design has small bridges between the poles [9]. These bridges also decrease stresses of the supporting magnets. Total thickness and length of the bridges between the two poles are 2.2 mm and 8 mm in the dovetail design and 6 mm and 10 mm in the V-shape design. Therefore, the leakage flux through the bridges is about three times smaller in the dovetail design when the bridges are magnetically unsaturated. In saturated situation, the difference of the leakage flux through the bridges between the designs becomes smaller. These phenomena can be seen in the larger difference between the no load currents and in the smaller difference between the load currents.

TABLE II
COMPARISON OF MAGNETS

Quantity	V-design	Dovetail design
Thickness (mm)	4.5	7.0
Area per pole (mm^2)	324	315
Total length in one pole (mm)	72	90
Total mass (kg)	2.44	2.37

The both motors under study are designed to operate at a speed of 6000 1/min and torque of 71.6 Nm. The common machine data is shown in Table I.

The magnet material, Neorem 495a, is sintered Nd–Fe–B [15]. Remanence and intrinsic coercivity of the used magnetic material in 20 ºC are 1.15 T and 2440 kA/m. Thermal dependence of remanence and intrinsic coercitivity are also be taken in the account with the factor as $1 + \alpha \cdot (T - 20ºC)$, where $\alpha = -0.0011$. Dimensions of the magnets are shown in Table II. In the dovetail design the effective magnetic thickness is smaller and the effective magnetic length is larger than in the V-shape design.

III. ELECTRICAL COMPARISONS OF DESIGNS

The dovetail and the V-shape prototype rotors have two main differences as different effective length and thickness of the magnets and different shape with different routes of the leakage flux. Therefore, the calculated properties of the prototype rotors are reasonable to compare also to a deep V-shape rotor with the same effective magnetic length and thickness as in the dovetail rotor (see Fig 2). The motor with the deep V-shape rotor is analyzed also with the half air gap between the magnets and the rotor stack, because only half of the total air gap is needed with the dovetail design compared to the V-shape design. Thicknesses of the supporting bridges of the all compared V-shape designs are the same, although in the deep V-shape solutions thicker radial bridges are needed to support the structure against centrifugal force.

First, visual comparisons of currents and efficiencies as a function of torque are performed first at a same voltage as

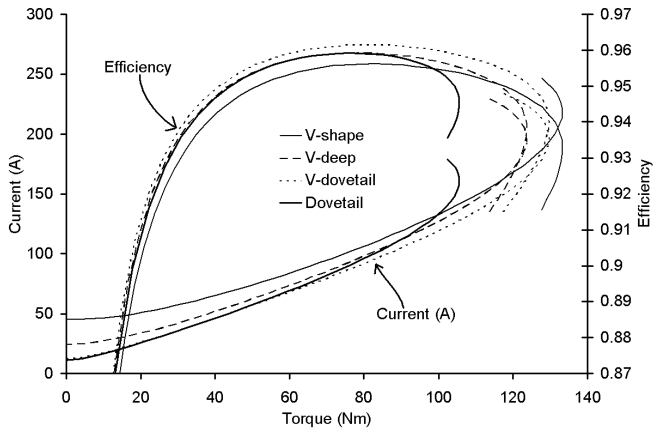

Fig. 3. Currents and efficiencies as a function of torque. Input voltage is 360V, and speed is 6000 1/min.

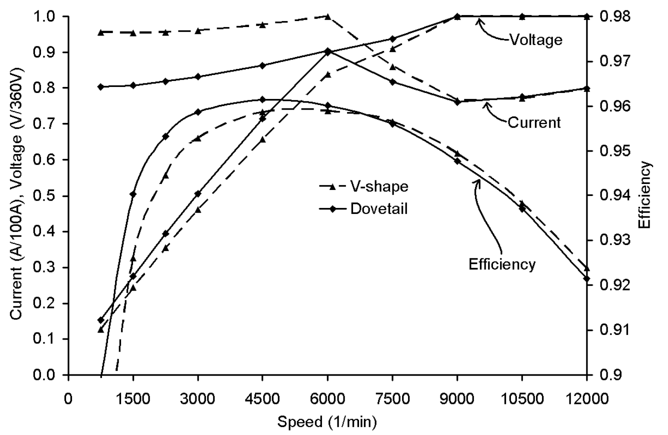

Fig. 4. Efficiencies, optimal voltages (V/360V) and currents (A/100A) as a function of speed. Machine has nominal torque below 6000 1/min and nominal power over 6000 1/min. Maximum voltage is 360V.

360V and a speed as 6000 1/min in Fig. 3. Lengthening and narrowing the magnets keeping the volume of the magnets same decreases the maximum torque but decreases also the no-load current and increases efficiencies ("V-deep" in Fig. 3). In practice, the modeled V-shape rotor with the long magnets is difficult to implement, because of the limited space between the shaft and the air gap. With the half of the total effective air gap between the magnets in the deep V-shape solution the maximum torque and the efficiencies are larger ("V-dovetail" in Fig. 3). However, although this V-shape solution is hard to manufacture and it is not durable enough for the speed as 6000 1/min, it has the best electrical properties of the all solutions considered.

The dovetail solution solves the difficulties in implementing longer magnets. In addition, the routes of the leakage flux have diminished and the number of air gaps between the magnets and rotor iron can be decreased to half. The dovetail solution decreases maximum torque and no load current and increases power factor further compared to the original V-shape design. Also, in the dovetail design, the tangential size difference of every second pole decreases the magnitude and the electric angle of the maximum torque.

Next, calculated open circuit voltages, nominal loads, no-load currents and maximum torques of the four designs were compared in the Table III. The nominal voltage 360 V is used in the all calculations. Assumed temperatures 65 ºC in the stator winding and 75 ºC in the magnets are used. Also

TABLE III
CALCULATED RESULTS FOR THE DOVETAIL, V AND DEEP V DESIGNS

Quantity	Dovetail	Dovetail sized V-shape	Deep V-shape	V-shape
Current (A)	84.1	81.6	87.4	96.5
Efficiency	95.91	96.11	95.9	95.56
Power factor	0.894	0.920	0.860	0.783
Total Losses (W)	1920	1789	1887	2055
Copper losses (W)	966	582	671	822
Iron losses (W)	634	887	896	913
Friction losses (W)	320	320	320	320
Open circuit (V)	327.4	329.0	301.2	262.5
No load current (A)	11.04	12.41	24.29	44.76
Max. Torque (Nm)	105.6	129.7	123.7	133.2
Max. Current (A)	159.5	197.6	194	217.6
Max. Torque Angle	75.4	97.6	98.5	105.7
THD of Torque (%)	6.16	5.42	5.22	5.51
THD of Current (%)	2.99	3.6	3.58	3.78

total harmonic distortions (THD) of torques and currents are compared.

Between the dovetail and the original V-shape design the open circuit voltage increase 23.6 percent. Therefore, for the optimized maximum efficiency, 6.5 percent larger supply voltage is also needed with the dovetail design. The efficiency of the dovetail design is slightly better that of the V-shape design while the difference of the power factors is greater. Also total harmonic distortion of the air gap torque and the line currents is smaller in the dovetail design.

Benefits of the dovetail design compared to the V-shape design can be seen clearly in the constant torque and the variable speed application. For illustrating that, efficiencies are optimized by voltages. Maximum voltage was 360V. Machines has constant torque below 6000 1/min and constant power above 6000 1/min. Resulted efficiencies, voltages and currents are shown in Fig. 4. The dovetail design has significantly better efficiency below nominal speed. For example, for application where whole speed range from 1500 1/min to 6000 1/min are equally used with the nominal torque, the total efficiencies of the V-shape and the dovetail designs are 95.4 percent and 95.8 percent, respectively. Corresponding values for 6000 1/min are 95.9 percent and 96.0 percent for the V-shape and the dovetail designs, respectively. Therefore the dovetail design is clearly electrically better for variable speed and constant torque applications than the V-shape design.

In conclusion, it is theoretically shown that, for the nominal speed, the dovetail design is electrically slightly better than the V-shape design, and for partial speeds with the nominal torque the dovetail design is significantly better than the V-shape design.

IV. FORCE COMPARISONS

The dovetail rotor has a totally different stress distribution compared to the V-shaped rotor. In the bridge fixed V-shaped rotor, most of the shear and tension stresses are in the iron bridges, whereas in the dovetail design, most of stresses are compression stresses in the supporting magnets. In the dovetail design, the bridges partly support the structure with the share of 50 percent of the total supporting force.

Von Mises stresses in the dovetail and the V-shaped designs are modeled with the FEM [14]. Computations are done using the centrifugal force associated at a speed of

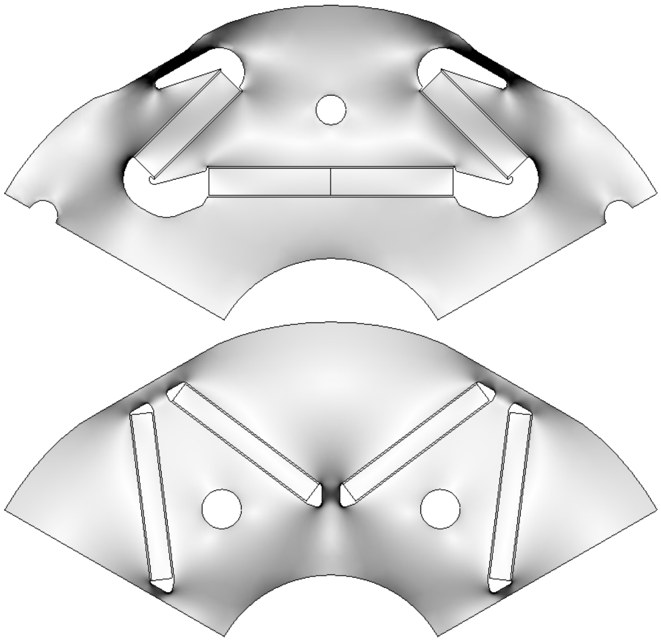

Fig. 5. Von Mises stress in the rotor with dovetail and V-design, at speed 6000 1/min. Light areas has lightest stresses starting form 0 MPa and black areas has stresses over 60 MPa.

6000 1/min, which correspond at a surface speed of 51 m/s with the rotor designs. Stress distributions are shown in Fig. 5. In the figures stresses are greatest in dark grey areas.

In the V-shape design, the largest stress 97 MPa is in the bridges of electrical steel sheets. This value is safe compared to the yield strength (305 MPa) of the steel. The maximum speed of rotors can be approximated with the equation

$$n_{\max} = n_{calc} \cdot \sqrt{\sigma_{yield} / (R_{calc} \cdot \eta)}, \tag{2}$$

where $n_{\max}$, n_{calc} , η , σ_{yield} , and R_{calc} are maximum speed, calculation speed, factor of safety, yield strength, and calculated critical stress.

Using a safety factor of 1.5, the maximum speed of the V-shape design is 8687 1/min. In the dovetail design, the largest and mechanically critical stress, 119 MPa, is localized in the tangential bridges of the sheets. These values are also below the yield strength (305 MPa) of the steel. The largest stress on the supporting magnets, 1.7 MPa, is far away from the critical strength of the magnets 75 MPa. Therefore, the maximum speed of the dovetail rotor is 7843 1/min with a safety factor of 1.5. In conclusion, both the dovetail and the V-shape designs are safely robust enough for the speed of 6000 1/min.

V. Tests

One motor with the both rotor type is tested with the similar stators. Test arrangement is shown in Fig. 6. The machine is attached to the fastening flange and the load machine with the gearing system is behind the fastening flange. Both machines are driven with a frequency converter [16] and the direct torque control (DTC). Temperatures of the stator end windings are defined with sensors during tests. The average temperature rise of the stator windings is defined with resistance measurements. Rotor temperatures are also defined during tests with the help of an induction signal transport system (shown in the right side of Fig.6). Voltages and currents are measured directly from terminals and saved and analyzed with an oscilloscope. Phase currents are measured between the delta connection and the motor. Some losses of the measurements are also defined. The total losses are defined from the measured input power and shaft torque. The current losses are defined from the measured currents and the winding temperatures. The friction losses are defined by rotating the machines with open connection. The test results are compared with the evaluated results.

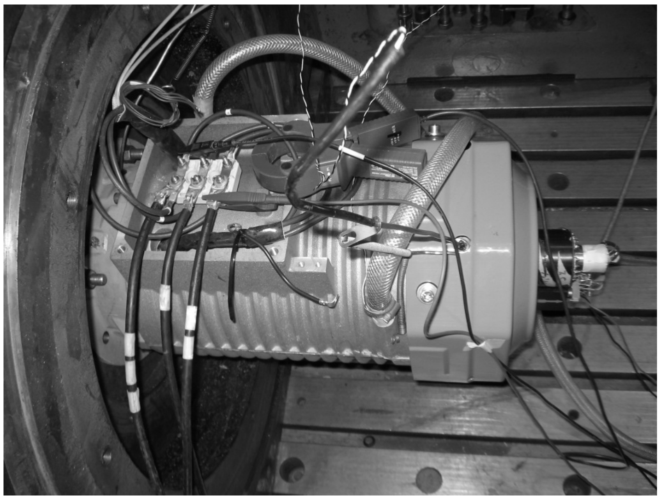

TABLE IV
OPEN CIRCUIT VOLTAGES

Quantity	Dovetail design	V-shape design
Evaluated Voltage (V)	356.8	301.6
Measured Voltage (V)	324.8	313.6

A. *Test history and mechanical durability of dovetail rotor*

The dovetail design is tested with the nominal and partial speeds with many loads. Test history with the nominal speed is following. Many short no-load tests are done first for the cold machine and then for the warm machine with the nominal operating temperature. After this, the load and the speed are to the nominal level and the motors are run for one and half hours. Then the motor is cooled down for 10 hours. Next, the machine is warmed up and load tests are done up to an overload of 50 kW. Finally, more no load tests are done with the cold machine.

The vibration level has remained small over all measurements at the same speed. There were no indications of increased vibration level. This indicates that the dovetail rotor maintains its balance. Also sub-sequential measurements give evidence that the vibration level was stationary; there is no plastic deformation in the rotor sheets and there are no fractures in the magnets. In conclusion, the tested dovetail rotor sustained speeds at least up to 6000 1/min.

B. *Open circuit voltage comparisons*

Open circuit voltages of the both machines are measured by running them with the load machine. The machine is driven at the speed of 6000 1/min. The temperature of the machines, in the all measured and evaluated cases considered, were 25 ºC. The open circuit voltages are

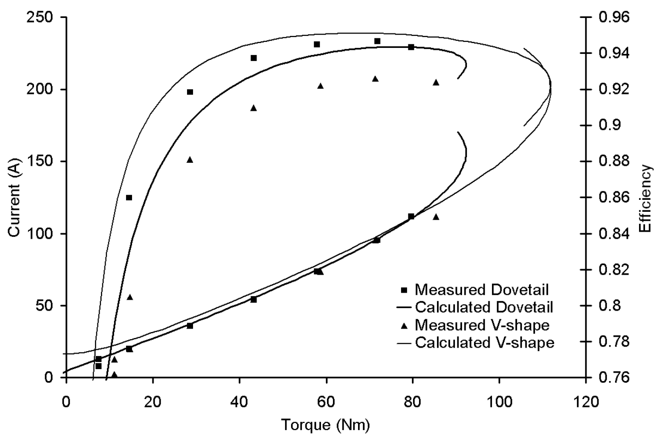

Fig. 7. Measured and calculated currents and efficiencies of dovetail design, at speed 6000 1/min and V-shape design, at speed 4500 1/min.

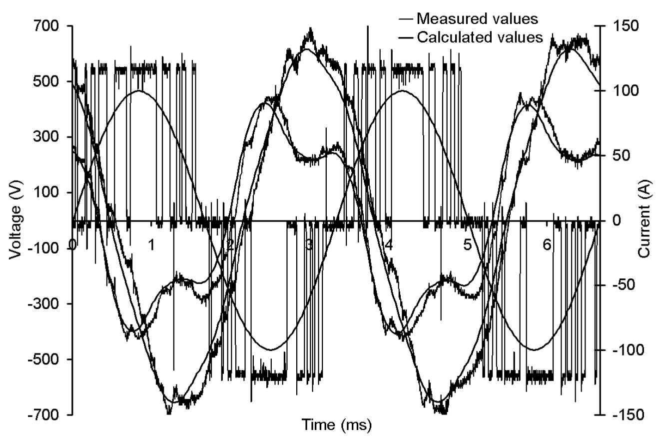

Fig. 8. Measured and calculated (smoother curves) voltages, phase currents and line currents of dovetail design, at speed 6000 1/min.

TABLE V
COMPARISON OF MEASURED AND CALCULATED VALUES FOR DOVETAIL AND V-SHAPE DESIGN AT SPEED 4500 1/MIN

Quantity	Dovetail Meas.	Dovetail Eval.	V-shape Meas.	V-shape Eval.
Shaft Power (kW)	33.82	33.91	33.64	33.75
Torque (Nm)	71.8	71.6	71.4	71.6
Voltage (V)	245.0	245.0	229.4	229.4
Current (A)	96.4	90.1	95.8	98.22
Efficiency (%)	93.25	94.74	93.16	94.56
Power factor	0.887	0.850	0.948	0.915
Total Losses (W)	2450	1882	2470	1942
Copper losses (W)	707	509	699	795
Iron losses (W)		673		447
Friction losses(W)	700	700	500	700
Stator winding (K)	35	40	39	40
Rotor magnets(K)	50	50	48	50
Ambient (ºC)	25	25	25	25

TABLE VI
COMPARISON OF MEASURED AND CALCULATED VALUES FOR DOVETAIL DESIGN AT SPEED 6000 1/MIN

Quantity	Dovetail, Measured	Dovetail, Evaluated
Shaft Power (kW)	45.69	44.97
Torque (Nm)	72.7	71.6
Voltage 1. harm (V)	324.3	329.2
Current (A)	98.77	95.98
Efficiency (%)	93.75	94.34
Power factor	0.878	0.871
Total Losses (W)	3045	2698
Copper losses (W)	809	764
Iron losses (W)		874
Friction losses (W)	1060	1060
Stator winding (K)	40	40
Rotor magnets (K)	50	50
Ambient (ºC)	25	25

measured with the open connection (with separate phase windings). However, they can also be measured with the delta connection, when measured voltages are seen to be under 0.4 percent smaller. The measured open circuit voltages of the V-shape and the dovetail designs are compared to calculated ones in Table IV.

The evaluated voltage with the dovetail design is 18.3 percent greater and the measured voltage is only 3.6 percent greater. These differences can be assumed to cause by manufacturing and measuring deviations, and by saturation errors in the calculations. Similar effects can also be seen in the other results shown later. In conclusion, the open circuit voltage is shown to be greater in the dovetail design than in the V-shape design.

C. Temperature rise test comparisons at a speed of 4500 1/min

First temperature rise tests of the both machines are performed at a speed of 4500 1/min and at an output power of 37.75 kW. Results are also compared with the modeled results in Table V. In all measurements, first harmonics of supply voltages were defined. Calculations are performed with the resulted sinusoidal-shaped voltages.

The friction losses are defined with the slowing-down test, where the machine is allowed to slow down freely. However, the friction losses defined with the slowing-down method include also some iron losses. The measured friction losses in the dovetail rotor are larger than in the V-shaped rotor due to different cooling wings in the ends of the rotors. However, the difference between the cooling wings has only a small effect to the final temperature rises of the designs.

In the dovetail design, the measured and evaluated efficiencies are greater than in the V-shape design as 0.09 and 0.18 percent, respectively. The measured smaller temperature rise with the dovetail design also supports the efficiency results. However, with the dovetail design, the evaluated current is smaller that the measured current, while with the V-shape design, the measured current is larger that the evaluated current.

Therefore, with the voltages chosen by the frequency converter with the DTC software, the measured and the modeled electrical losses of the designs are near each other. However, the evaluated losses are smaller than the measured losses. With the sinusoidal supply voltage in the calculations, the resulted losses are smaller than with the real supply voltage produced by the frequency converter.

Differences between the calculated and measured results can also be seen in Fig. 7, where currents and efficiencies of dovetail design, at speed 6000 1/min and V-shape design, at speed 4500 1/min with the different torque are compared to each others. These results indicate the reliability of the evaluating process.

In conclusion, the electrical properties are shown to be better in the dovetail design with the load and speed considered in this chapter.

D. Temperature rise test of the dovetail design at a speed of 6000 1/min

The machine with the dovetail design is tested further. A temperature rise test at a nominal speed of 6000 1/min and at a nominal power of 45 kW is performed. The other load points are also measured with the warm machine after the temperature rise test. The results are compared to evaluated ones.

Electrical properties of the test system are studied first by comparing the measured voltage, the phase current and the line current to the modeled ones in Fig. 8. The form of the measured line and phase currents follows modeled ones very well. The effect of the current circulating in the delta connection can be seen in the form of the phase current. There is clear third harmonics of the phase current.

The first harmonic of a measured voltage, supplied by the frequency converter with DTC, was 324.3 V. The calculation has performed at a voltage, which give the best calculated efficiency, as 329.2 V. Note, that these values are near to each others. In addition, the measured first harmonic of the supply voltage can be assumed to have right values, because the form of the measured and calculated phase currents follows each others so well.

The other measured load points, compared to the results, are calculated also at the voltage as 329.2V. The measured current values are near the modeled currents as a function of torque as can be seen in Fig. 7. However, the measured efficiencies are clearly larger than the modeled ones. The modeled electromagnetic losses are overestimated. In conclusion, the shown measured effects can be seen and the shown measured values can be estimated with the calculation procedure.

VI. Conclusion

The six-pole prototype motor with a dovetail-shaped magnet poles exhibits a significant increase in mechanical stability over the conventional V-pole design. By converting the tensile stress in the iron bridges into a compressive stress in the magnets by redesigning the pole geometry, a very robust construction can be achieved.

The electrical properties and the consumption of magnetic material can be kept at least at the same level as in the V-pole design. The dovetail design applications have also significantly better efficiencies when large speed range is needed.

In practice, this dovetail rotor design gives a viable solution to increase the speed range of synchronous permanent magnet machines with a transversally laminated rotor structure. Our design requires no extra supporting structures to counter the centrifugal forces and is consequently more straightforward to manufacture.

VII. Acknowledgment

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VIII. References

[1] B.K. Bose, "A high-performance inverter-fed drive system of an interior permanent magnet synchronous machine," *IEEE Trans. Ind. Appl.,* vol. 24, no.6, 987-997, Nov. 1988.

[2] A. Binder, T. Schneider, and M. Klohr, "Fixation of Buried and Surface Mounted Magnets in High-Speed Permanent-Magnet Synchronous Machines," *IEEE Trans. Ind. Appl.,* vol. 42, no.4, 1031-1037, Jul./Aug. 2006.

[3] J. Gan, K.T. Chau, C.C. Chan, and J.Z. Jiang, "A New surface-inset, permanents-magnet, brushless dc motor drive for electric vehicles," *IEEE Trans. Mag.,* vol. 36, no.5, 3810-3818, Sep. 2000.

[4] M.W. Degner, R. van Maaren, A. Fahim, D.W. Novotny, R. D. Lorenz, and C.D. Syverson, "A rotor lamination design for surface magnet retention at high speeds," *IEEE Trans. Ind. Appl.,* vol. 32, no.2, 380-385, Mar./Apr. 1996.

[5] E.C. Lovelace, T.M. Jahns, T.A. Keim, and J.H. Lang, "Mechanical design considerations for conventionally laminated, high speed, interior PM synchronous machine rotors," *IEEE Trans. Ind. Appl.,* vol. 40, no.3, 806-812, May/June 2004.

[6] C.-C. Hwang, and Y.H. Cho, "Effects of leakage flux on magnetic fields of interior permanent magnet synchronous motors," *IEEE Trans. Magn.,* vol. 37, no.4, 3021-3024, July 2001.

[7] J. Kolehmainen, "Machine with a rotor structure supported only by buried magnets," *in ISEF, Prague, Czech Republic*, Sep. 2007.

[8] S. Wiak, A. Krawczyk, and I. Dolezel, Eds.,"Advanced Computer Techniques in Applied Electromagnetics" vol. 30, Studies in Applied Electromagnetics and Mechanics. Amsterdam, The Netherlands: IOS Press, 2008.

[9] J. Kolehmainen, and J. Ikäheimo, "Motors with buried magnets for medium speed applications," *IEEE Trans. Energy Convers.,* vol. 23, no.1, 86-91, Mar. 2008.

[10] J. Kolehmainen, "Dovetail permanent magnet rotor solutions with different pole numbers," Paper ID 939, *in ICEM, Vilamoura, Portugal*, Sep. 2008.

[11] J. Kolehmainen, "Optimal dovetail permanent magnet rotor solutions with different pole numbers," *IEEE Trans. Ind. Electrl.,* vol. 57, no.1, 70-77, Jan. 2010.

[12] J. Kolehmainen, "Rotor for a permanent-magnet electrical machine," WO Patent 2008025873 (A1), Mar. 6, 2008, and FI Patent 119457 (B1), Nov. 14, 2008.

[13] A. Arkkio, "Analysis of induction motors based on the numerical solution of the magnetic field and circuit equations," Ph.D. thesis, Acta Polytechnica Scandinavica, no. 59, 1987.

[14] COMSOL Multiphysics software. (2009). [Online]. Available: www.comsol.com

[15] Neorem495s by Neorem Magnets – www.neorem.fi.

[16] ACS 607-0400-5, frequency converter – www.abb.com.

IX. Biography

Jere Kolehmainen received the M.Sc. and Ph.D. degrees in theoretical physics from University of Jyväskylä, Jyväskylä, Finland in 1996 and 2000, respectively.

Currently, he is working at ABB Oy, Motors in Vaasa, Finland. He is interested in synchronous and induction AC machines and electromagnetic modeling.