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## MACHINE WITH A ROTOR STRUCTURE SUPPORTED ONLY BY BURIED MAGNETS

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***Abstract** — A buried magnet rotor structure, which is supported only by permanent magnets, is proposed for medium speed permanent magnet machines. A machine utilizing the construction is built, tested and compared to another machine with traditional V-shaped poles. The machine is also simulated using Finite Element Method and the results are compared to tested values. The obtained results demonstrate the feasibility of the construction.*

### Introduction

Permanent magnet synchronous machines (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. With a buried magnet design flux concentration can be achieved, which induces higher air gap flux density [1-2]. That, in turn, gives a possibility to increase torque of a machine.

The typical way of manufacture a buried PM rotor is to assemble a stack of punched rotor disks with rectangular holes and insert magnets into these holes. The rotor poles between the magnets are fixed to rest of the rotor structure with thin iron bridges. The disadvantage of the supporting bridges is the leakage flux, the magnitude of which depends on the thickness of the bridges. In low speed applications this is not a problem, since the centrifugal forces acting on the poles are relatively small and the bridges can be kept thin. However, as the tangential speed of the rotor surface in medium speed applications (4000...8000 1/min) exceeds 60 m/s (corresponding to 4000 1/min in machine size IEC250) the stress in the bridges will exceed the yield strength of the electrical steel (typically 300 MPa for grade M400-50A). The problem can be countered by increasing the thickness of the bridges, however, this increases the leakage flux, which in turn increases the amount of magnet material needed to get the required torque.

However, there exists a solution with thinner bridges, where magnets are partly used to support the pole structure [3]. In this paper we go further and study a solution on how to get mechanically more robust rotor structures without using iron bridges. In the solution the tensile stress is geometrically converted into compressive one and only the magnets are used to support the pole structure. The new solution is compared to a traditionally used solution with V-shaped poles. The comparison is done using time stepping and static calculations using Finite Element Method (FEM) [4]. Machines with both the rotor designs are built and tested. The machine with the new dovetail pole design is analyzed further and results are compared to simulations.

## Machine Designs

An 8-pole machine with V-shaped rotor poles is used as an example for comparison to a machine with the new dovetail design without supporting bridges. The machine has shaft height 250 mm, nominal power 110 kW, voltage 370 V, and speed 4800 1/min. The only difference of the two machines is in their rotor structure as it can be seen in Fig. 1. An 8-pole machine has 8 symmetry sections in V-pole design, but in the dovetail design the rotor has magnets in every second pole [1].

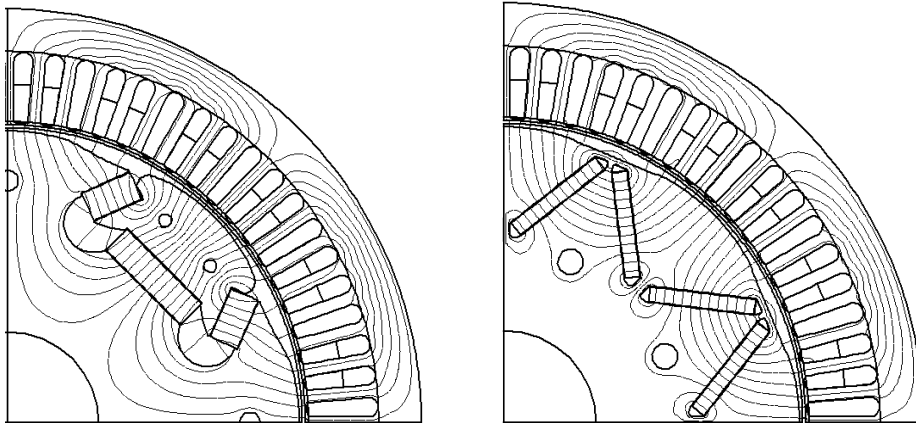


Fig. 1. Designs with dovetail and V shaped poles with flux lines created by the flux of the magnets.

With both designs, volume of the magnets and dimensions of the magnets seen by stator are same. With the V shape design, total magnet width and length in one pole are  $2 \times 7.3 = 14.6$  mm and  $52 + 52 = 104$  mm and with the dovetail design, these are  $1 \times 14.6 = 14.6$  mm and  $26 + 52 + 26 = 104$  mm. Length of the both rotors is 120 mm. Magnetically, there are two major differences which affect to electrical properties of machines. The dovetail design has not magnetic bridges between poles so the leakage flux is reduced especially with low saturation of flux. Every second pole of the dovetail design has a different tangential air gap length so electrical properties with high load angles are expected to be slightly worse than with the V shape design.

## Manufacturing

Two machines with both rotor types are manufactured. The general method to manufacture the rotor with a V shaped design is to assemble a stack of disks, compress it using bolts and nonmagnetic end plates and shrink fit the stack on the shaft. Then, the magnets are inserted into their holes using glue. The rotor with the dovetail design is manufactured with a different method, which is to assemble five (one central body and four small poles) stacks of disks, compress them using bolts and nonmagnetic end plates and shrink fit the central body stack on the shaft. Next, the magnets are fixed to four pole stacks using glue. Resulting poles are axially inserted to central body stack using glue.



Fig. 2. Manufacturing rotor with dovetail design. In the left there is a pole with magnets, in the middle there is the rotor without the pole, and in the right the pole is inserted to rotor.

## Results

The machines with the both designs are tested and analyzed. For all load tests, as for our industrial cases, the direct torque control strategy with software for permanent magnet AC machines is used with frequency converter ACS600 [5]. All electromagnetic calculations are done with time stepping Finite Element Method [4]. In load calculations, voltage source is used, the form of the voltage is sinusoidal and amplitude is kept the same. Simulations are started with various rotor angles without initial solution and stopped after 41 electric periods when transient oscillations have totally died away. Constant rotor speed is used. Iron losses are calculated from the equation

$$P_{TOT} = k_h B_m^2 f + \frac{1}{T} \int_0^T \left[ \sigma \frac{d^2}{12} \left( \frac{dB}{dt}(t) \right)^2 + k_e \left( \frac{dB}{dt}(t) \right)^{3/2} \right] k_f dt, \quad (1)$$

where  $B_m$  is the maximum flux density at the node concerned,  $f$  is the frequency,  $\sigma$  is the conductivity,  $d$  is the lamination thickness,  $k_h$  is the coefficient of hysteresis loss and  $k_e$  is the coefficient of excess loss.

### Open Circuit Voltage

Measured open circuit voltages of both machines, at speed 4800 1/min, are compared to the calculated ones in the Table I. The measuring and the calculating temperature has been 20 °C. In this case, the magnets have a remanence flux density of 1.1 T and energy product 230 kJ/m<sup>3</sup>.

TABLE I. OPEN CIRCUIT VOLTAGES

Quantity	Dovetail design	V-shape design
Measured voltage (V)	311.1	330.5
Calculated voltage (V)	365.5	347.6

The dovetail design has 5.2 % larger calculated open circuit voltage than the V shape design. The measured open circuit voltage is 4.9 % smaller than calculated for the V shape design and it is 14.9 % smaller for the dovetail design. The measured open circuit voltages were expected to be smaller, because small rotor length and diameter ratio ( $120 / 289 = 0.42$ ) causes remarkable leakage fluxes in ends of rotors. With the dovetail design, also axial deviations of the rotor will add leakage fluxes (the rotor body is slightly longer than the poles). The machine with the dovetail design has also different harmonic distribution of open circuit voltage, as can be seen in Fig. 3. The fifth harmonic is almost same with both designs. The seventh, eleventh and thirteenth harmonics are larger with the dovetail design while the fifth, seventeenth and nineteenth harmonics are larger with the V shape design. This is caused by different air gap forms and different sizes of every second pole with dovetail design. Practically, voltage and torque ripples are on the same level.

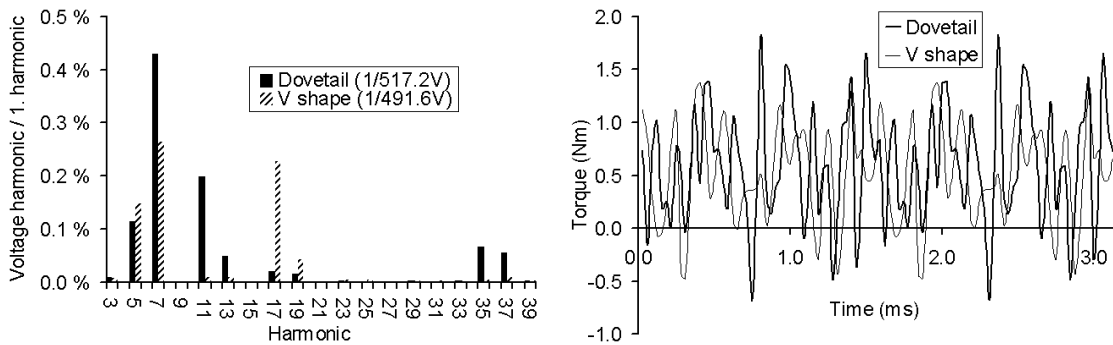


Fig. 3. Open voltage harmonics and torque ripples with speed 4800 1/min of dovetail and V shape designs.

## Calculated Electrical Properties with Different Loads

The calculated electrical properties as a function of electric load angle are compared in Fig. 4. With the dovetail design the torque is sinusoidal; the reluctance torque is negligible and the maximum torque 382 Nm with load angle 90 degrees is smaller than torque (414 Nm) with the V shape design, because of asymmetric pole pairs. With the V shape design, maximum torque is 426 Nm at load angle 102 degrees. Furthermore, maximum reluctance torque is 49 Nm. In addition, the current behaves differently, because of different saturation. With the dovetail design, power factor is larger with electric load angles under 55 degrees and with higher load angles, it is slightly smaller. However, efficiencies are slightly better with the V shape design.

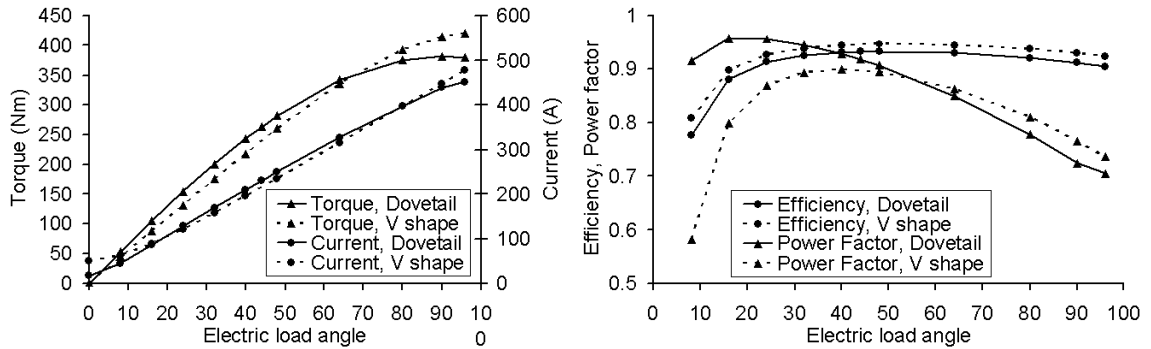


Fig. 4. Calculated torque and current (left) and efficiency and power factor (right) as a function of electric load angles with dovetail and V shape design.

## Comparisons with Different Loads

Measured input and output powers as a function of current are compared to calculated ones in Fig. 5. Generally, measured powers are smaller than calculated powers. The possible reason is the same than with the case of voltages; leakage fluxes in the ends of rotors. Difference is also bigger with the dovetail design. Same differences can be seen in comparison of nominal load results.

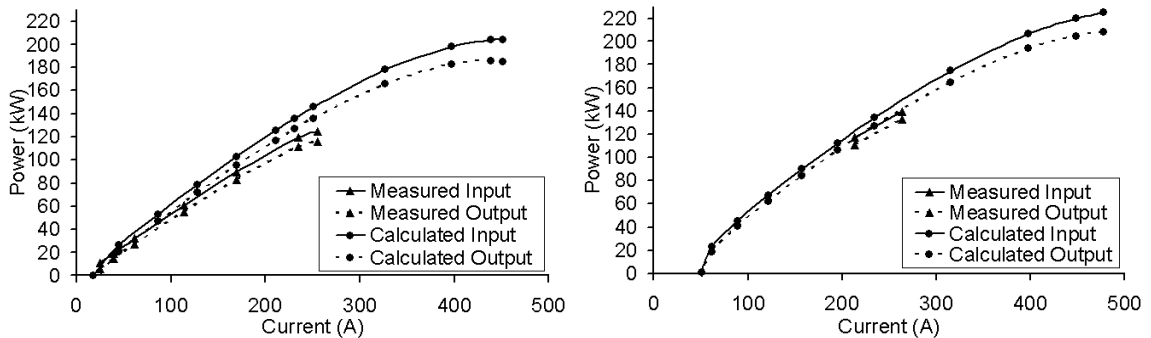


Fig. 5. Calculated and measured input and output power with dovetail (left) and V shape (right) designs as a function of current.

## Nominal load

The measured and the calculated nominal load results of the two designs are compared in the Table II. Used stator winding temperature is 75 °C. Approximated “Other Losses” contains all other losses except friction and additional losses. Iron losses are calculated with equation (1). All efficiencies have the same magnitude. With the dovetail design, the calculated power factor is 4.1 % better and measured power factor is 7.8 % worse than with the V shape design.

TABLE II. COMPARISON OF NOMINAL LOAD RESULTS

Quantity	Measured	Calculated	Measured	Calculated
	Dovetail design	Dovetail design	V-shape design	V-shape design
Shaft Power (kW)	110.2	110.4	111.1	110.3
Torque (Nm)	219.1	219.6	221.0	219.5
Voltage (V)	370	370	370	370
Current (A)	229.7	194.0	212.9	202.8
Efficiency	0.947	0.950	0.950	0.946
Power Factor	0.791	0.935	0.858	0.898
Total Losses (kW)	6.26	6.26	5.90	6.03
Copper Losses (kW)	1.66	1.19	1.30	1.18
Total - Copper (kW)	4.60	5.08	4.60	4.85
Iron Losses (kW)		1.50		1.27
Other Losses (kW)		3.58		3.58

Torque oscillations are compared with different electric load angles in Fig. 6. The oscillations are larger with the dovetail design and calculated load angles over 8 degrees. Oscillation is studied further with load angle 40 degrees in Fig. 6. Clear sixth order torque harmonics can be seen with the dovetail design. With the V shape design, remarkable twelfth order torque harmonic reduces total oscillation.

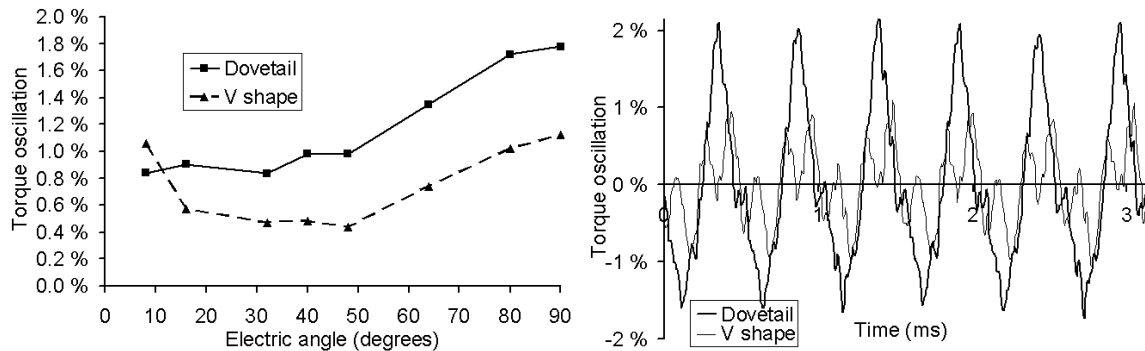


Fig. 6. Calculated torque oscillations as a function of electric angle (left) and torque as a function of time with electric load angle 40 degrees (right) with dovetail and V shape designs.

## Strength of structures

### Stress Analysis

The rotor with the new dovetail design has a totally different stress distribution compared to the V-pole rotor. In the V-pole rotor, all of the shear and tension stresses are in the iron bridges whereas in the dovetail design, most of stresses are compression stress in the magnets and shear stress near corners of magnets. Von Mises stresses in the dovetail and in the V shape designs with are shown in Fig. 7. Computation is done using the centrifugal force associated with the speed of 4800 1/min. The largest stress in electric steels of the dovetail design, 130 MPa, is locally in the corners of sheets. With the V shape design, average stress in the inner bridges is 90 MPa and the largest stress in electric steels, 200 MPa, is also locally in the corners of sheets. These values are below the yield strength (305 MPa) of the steel. With the dovetail design, in center of the smaller magnets the stress is 50 MPa. It is well below the maximum compressive strength of the magnets. The calculated maximum stress in magnets is 381 MPa (located in corners). Using magnets to compose the structure it becomes robust enough for the speed of 4800 1/min.

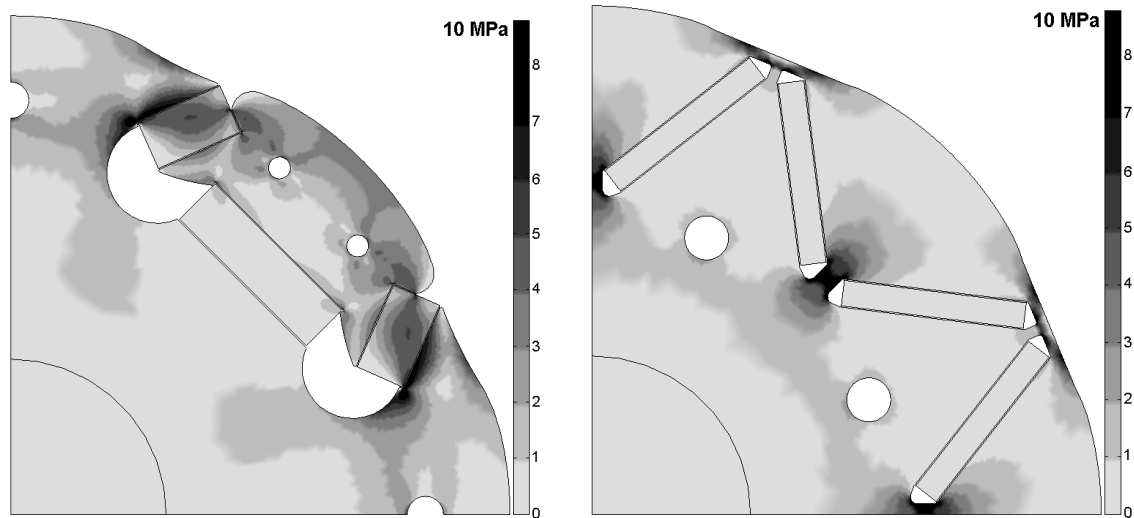


Fig. 7. Von Mises stress with speed 4800 1/min. The stresses are greatest in dark grey areas.

### Stability of rotor with dovetail design

The mechanical durability test of the motors consists of two load runs with speed 4800 1/min. First, the motor is driven with different loads and operating temperatures for one and half hours. After this, the motor was cooled over night. Finally, temperature test has done for four and half hours. Measured vibration levels remained same thought all tests. Visual check was done after test. The magnets remained solid. The glue seam between inner magnets and rotor body was separated. In the sides of smaller magnets, glue was changed its color from grey to light grey. This indicate that glue was deformed, not separated. Hence, stability of the rotor remained, but more tests should be done to see whether stability remains with longer period.

### Conclusion

The prototype machine 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 on the same level as in the V-pole design.

### References

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